THE UNIVERSE AROUND US

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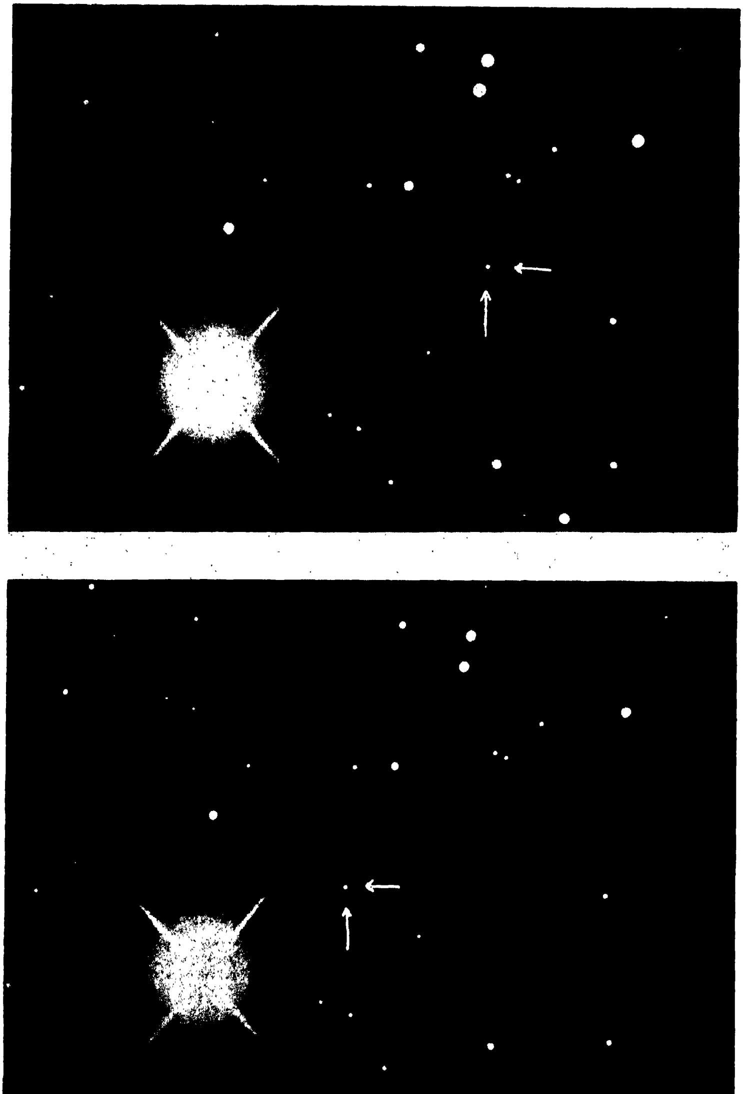

Lowell Observatory

The Discovery of Pluto

The two photographs were taken at the Lowell Observatory on the nights of March 2 and 5, 1930. The object indicated by arrows was seen to have moved considerably in the interval, and this proved that it was of planetary character.
The bright object in the bottom left-hand corner is the star δ Geminorum (see p. 280).

THE UNIVERSE AROUND US

By

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PREFACE

The present book contains a brief account, written in simple language, of the methods and results of modern astronomical research, both observational and theoretical. Special attention has been given to problems of cosmogony and evolution, and to the general structure of the universe. My ideal, perhaps never wholly attainable, has been that of making the entire book intelligible to readers with no special scientific knowledge.

Parts of the book cover the same ground as various lectures I have recently delivered to University and other audiences, including a course of wireless talks I gave last autumn. It has been found necessary to rewrite these almost in their entirety, so that very few sentences remain in their original form, but those who have asked me to publish my lectures and wireless talks will find the substance of them in the present book.

J. H. JEANS

DORKING
1 *May* 1929

PREFACE TO SECOND EDITION

In preparing a second edition, I have taken advantage of a great number of suggestions made by correspondents and reviewers, to whom I offer my sincerest thanks. I have also inserted discussions of the new planet Pluto, the rotation of the galaxy, the apparent expansion of the universe, and other subjects which have become important since the first edition was published, and in general have tried to bring the book up to date.

J. H. JEANS

DORKING
2 *August* 1930

PREFACE TO THIRD EDITION

The three years which have elapsed since the second edition of this book appeared have been more than usually eventful for those parts of science with which the book deals.

At the sub-atomic end of the scale of nature, the uncharged neutron and the positively-charged electron have been discovered—in a world which had hitherto been believed to consist solely of positively-charged protons and negatively-charged electrons. At the other end of the scale there is much new knowledge, both observational and theoretical, on the expansion of the universe and cosmic radiation. In the intermediate parts of the scale, in addition to a large mass of new observational material, we find new spectroscopic methods for investigating the constitution and rotations of the stars, and new theoretical discussions of their structure. From these and other causes, the present edition is substantially longer than its predecessors.

I have to thank various friends and correspondents for a number of valuable suggestions and criticisms, and in particular Mr W. F. Sedgwick, sometime of Trinity College, Cambridge, who has checked most of my calculations and suggested many improvements.

J. H. JEANS

DORKING

7 *October* 1933

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The Study of Astronomy

On the evening of January 7, 1610, a fateful day for the human race, Galileo Galilei, Professor of Mathematics in the University of Padua, sat in front of a telescope he had made with his own hands.

More than three centuries previously, Roger Bacon, the inventor of spectacles, had explained how a telescope could be constructed so as "to make the stars appear as near as we please." He had shewn how a lens could be so shaped that it would collect all the rays of light falling on it from a distant object, bend them until they met in a focus, and then pass them on through the pupil of the eye on to the retina. Such an instrument would increase the power of the human eye, just as an ear trumpet increases the power of the human ear by collecting all the waves of sound which fall on a large aperture, bending them, and passing them through the orifice of the ear on to the ear drum.

Yet it was not until 1608 that the first telescope had been constructed by Lippershey, a Flemish spectacle-maker. On hearing of this instrument, Galileo had set to work to discover the principles of its construction and had soon made himself a telescope far better than the original. His instrument had created no small sensation in Italy. Such extraordinary stories had been told of its powers that he had been commanded to take it to Venice and exhibit it to the Doge and Senate. The citizens of Venice had then seen the most aged of their Senators climbing the highest bell-towers to spy through the telescope at ships which were too far out at sea to be seen at all without its help. The telescope admitted about a hundred times as much light as the

unaided human eye, and Galileo claimed that it shewed objects fifty miles distant as clearly as though they were only five miles away.

Perhaps it need hardly be said that this power is quite insignificant in comparison with that of modern instruments. The telescope of 100-inch aperture at Mount Wilson, California, the largest at present in existence, admits 2500 times as much light as Galileo's tiny instrument, and so 250,000 times as much light as the unaided eye. A telescope of double this aperture, which will shortly be built in California, will admit four times as much light as the 100-inch instrument, or about a million times as much light as the unaided eye.

The absorbing interest of his new instrument had almost driven from Galileo's mind a problem to which he had at one time given much thought. Over two thousand years previously, Pythagoras and Philolaus had taught that the earth is not fixed in space but rotates on its axis every twenty-four hours, thus causing the alternation of day and night. Aristarchus of Samos, perhaps the greatest of all the Greek mathematicians, had further maintained that the earth not only turned on its axis, but also described a yearly journey round the sun, this being the cause of the cycle of the seasons.

Then these doctrines had fallen into disfavour. Aristotle had pronounced against them, asserting that the earth formed a fixed centre to the universe. At a later date Ptolemy had explained the tracks of the planets across the sky in terms of a complicated system of cycles and epicycles; the planets moved in circular paths around moving points, which themselves moved in circles around an immoveable earth. The Church had given its sanction and active support to these doctrines. Indeed, it is difficult to see what else it could have done, for it seemed almost impious to sup-

pose that the great drama of man's fall and redemption, in which the Son of God had Himself taken part, could have been enacted on any lesser stage than the very centre of the Universe.

Yet, even in the Church, the doctrine had not gained universal acceptance. Oresme, Bishop of Lisieux, and Cardinal Nicholas of Cusa had both declared against it, the latter writing in 1440:

> I have long considered that this earth is not fixed, but moves as do the other stars. To my mind the earth turns upon its axis once every day and night.

At a later date such views incurred the active hostility of the Church, and in 1600 Giordano Bruno was burned at the stake, one of the counts against him being his insistence on the doctrine of the plurality of worlds. He had written:

> It has seemed to me unworthy of the divine goodness and power to create a finite world, when able to produce beside it another and others infinite; so that I have declared that there are endless particular worlds similar to this of the earth; with Pythagoras I regard it as a star, and similar to it are the moon, the planets and other stars, which are infinite in number, and all these bodies are worlds.

The most weighty attack on orthodox doctrine had, however, been delivered neither by theologians nor philosophers, but by the Polish astronomer, Nicolaus Copernicus (1473–1543). In his great work *De revolutionibus orbium coelestium* Copernicus had shewn that Ptolemy's elaborate structure of cycles and epicycles was unnecessary, because the tracks of the planets across the sky could be explained in a much simpler manner by supposing that the earth and the planets all moved round a fixed central sun. The sixty-six years which had elapsed since this book was published had seen these theories hotly debated, but they

were still neither proved nor disproved. And although Galileo found himself powerfully attracted to them, he had hitherto thought it the more prudent course to keep his opinions to himself.

Galileo had already found that his new telescope provided a means of testing astronomical theories. As soon as he had turned it on to the Milky Way, a whole crowd of legends and fables as to the nature and structure of this object had vanished into thin air; it proved to be nothing more than a swarm of faint stars scattered like golden dust on the black background of the sky. Another glance through the telescope had disclosed the true nature of the moon. It had on it mountains which cast shadows, and so proved, as Giordano Bruno had maintained, to be a world like our own. What if the telescope should now in some way prove able to decide between the orthodox doctrine that the earth formed the hub of the universe, and the revolutionary new doctrine that the earth was only one of a number of bodies, all circling round the sun like moths round a candle-flame?

And now Galileo catches Jupiter in the field of his telescope and sees four small bodies circling around the great mass of the planet—like moths round a candle-flame. What he sees is an exact replica of the solar system as imagined by Copernicus, and it provides direct visual proof that such systems are at least not alien to the architectural plan of the universe. On January 30th he writes to Belisario Vinta that these small bodies move round the far greater mass of Jupiter "just as Venus and Mercury, and perhaps the other planets, move round the sun."

Any lingering doubts that Galileo may have felt as to the significance of his discovery are removed nine months later when he observes the phases of Venus; the shining surface of the planet was seen to pass

through the same cycle of shapes as the moon—from crescent through semicircle to a full circle, and then, reversing the paths, back through semicircle to crescent. This of course shewed at once that the planet was not self-luminous, since had it been so, its surface would always have appeared as a full circle of light. Even so two distinct alternatives remained. If Venus, not being self-luminous, moved round the earth in a Ptolemaic epicycle, then, as Ptolemy had himself pointed out, she could never shew more than half her surface illuminated. If, on the other hand, as the new Copernician view required, she moved round the sun in a circle, while the earth also moved round the sun in a larger circle, then the shining surface of Venus ought to exhibit the complete sequence of phases shewn by the moon, the surface of the planet appearing completely dark at the moment when it passed between the earth and the sun. And the same ought to be true also of Mercury. It had indeed been urged as an objection to the Copernician theory that neither Venus nor Mercury exhibited this full cycle of phases.

Galileo's telescope now shewed that, precisely as Copernicus had foretold, Venus passed through the full cycle of phases, so that, in Galileo's own words, we "are now supplied with a determination most conclusive, and appealing to the evidence of our senses, of two very important problems, which up to this day have been discussed by the greatest intellects with different conclusions. One is that the planets are not self-luminous. The other is that we are absolutely compelled to say that Venus, and Mercury also, revolve around the sun, as do also all the rest of the planets, a truth believed indeed by the Pythagorean school, by Copernicus, and by Kepler, but never proved by the evidence of our senses, as is now proved in the case of Venus and Mercury."

These discoveries of Galileo made it clear that Aristotle, Ptolemy and the majority of those who had thought about these things in the last 2000 years had been utterly and hopelessly wrong. In estimating his position in the universe, man had up to now been guided mainly by his own desires, and his self-esteem; long fed on boundless hopes, he had spurned the simpler fare offered by patient scientific thought. And now inexorable facts dethroned him from his self-arrogated station at the centre of the universe; henceforth he must reconcile himself to the humble position of the inhabitant of a speck of dust, and adjust his views as to the significance and importance of human life accordingly.

The adjustment was not made at once. Human vanity, reinforced by the authority of the Church, contrived to make a rough road for those who dared draw attention to the earth's insignificant position in the universe. Galileo was forced to abjure his beliefs. Well on into the eighteenth century the ancient University of Paris was teaching that the motion of the earth round the sun was a convenient *but false* hypothesis, while the newer American Universities of Harvard and Yale taught the Ptolemaic and Copernican systems of astronomy side by side as though they were equally tenable. Yet men could not keep their heads buried in the sand for ever, and when at last its full implications were accepted, the revolution of thought initiated by Galileo's observations of January 7, 1610, proved to be the most catastrophic in the history of the race. The cataclysm was not confined to the realms of abstract thought; henceforth human existence itself was to appear in a new light, and human aims and aspirations would be judged from a different standpoint.

This oft-told story has been told once again, in the

hope that it may serve to explain some of the interest taken in astronomy to-day. The more mundane sciences prove their worth by adding to the amenities and pleasures of life, or by alleviating pain or distress, but it may well be asked what reward astronomy has to offer. Why does the astronomer devote arduous nights, and even more arduous days, to studying the structure, motions and changes of bodies so remote that they can have no conceivable influence on human life?

In part at least the answer would seem to be that many have begun to suspect that the astronomy of to-day, like that of Galileo, may have something to say on the enthralling question of the relation of human life to the universe in which it is placed, and on the beginnings, meaning and destiny of the human race. Bede records how, some twelve centuries ago, human life was compared in poetic simile to the flight of a bird through a warm hall in which men sit feasting, while the winter storms rage without.

> The bird is safe from the tempest for a brief moment, but immediately passes from winter to winter again. So man's life appears for a little while, but of what is to follow, or of what went before, we know nothing. If, therefore, a new doctrine tells us something certain, it seems to deserve to be followed.

These words, originally spoken in advocacy of the Christian religion, describe what is perhaps the main interest of astronomy to-day. Man

> only knowing
> Life's little lantern between dark and dark

wishes to probe farther into the past and future than his brief span of life permits. He wishes to see the universe as it existed before man was, as it will be after the last man has passed again into the darkness

from which he came. The wish does not originate solely in mere intellectual curiosity, in the desire to see over the next range of mountains, the desire to attain a summit commanding a wide view, even if it be only of a promised land which he may never hope himself to enter; it has deeper roots and a more personal interest. Before he can understand himself, man must first understand the universe from the dust of which his body has been formed, and from the events of which all his sense perceptions are drawn. He wishes to explore the universe, both in space and time, because he himself forms part of it, and it forms part of him.

We may well admit that science cannot at present hope to say anything final on the questions of human existence and human destiny, but this is no justification for not becoming acquainted with the best that it has to offer. It is rare indeed for science to give a final "Yes" or "No" answer to any question propounded to her. When we are able to put a question in such a definite form that either of these answers could be given in reply, we are generally already in a position to supply the answer ourselves. Science advances rather by providing a succession of approximations to the truth, each more accurate than the last, but each capable of endless degrees of higher accuracy. To the question, "where does man stand in the universe?" the first attempt at an answer, at any rate in recent times, was provided by the astronomy of Ptolemy: "at the centre." Galileo's telescope provided the next, and incomparably better, approximation: "man's home in space is only one of a number of small bodies revolving round a huge central sun." Nineteenth-century astronomy swung the pendulum still farther in the same direction, saying: "there are millions of stars in the sky, each similar to our sun, each doubtless surrounded, like our sun, by a family

of planets on which life may be kept in being by the light and heat received from its sun." Twentieth-century astronomy suggests, as we shall see, that the nineteenth century had swung the pendulum too far; life now seems to be more of a rarity than our fathers thought, or would have thought if they had given free play to their intellects.

We are setting out to explain the approximation to the truth provided by twentieth-century astronomy. No doubt it is not the final truth, but it is a step on towards it, and unless we are greatly in error it is very much nearer to the truth than was the teaching of nineteenth-century astronomy. It claims to be nearer the truth, not because the twentieth-century astronomer claims to be better at guessing than his predecessors of the nineteenth century, but because he has incomparably more facts at his disposal. Guessing has gone out of fashion in science; it was at best a poor substitute for knowledge, and modern science, eschewing guessing severely, confines tself, except on very rare occasions, to ascertained facts and the inferences which, so far as can be seen, follow unequivocally from them.

It would of course be futile to pretend that the whole interest of astronomy centres round the questions just mentioned. Astronomy offers at least three other groups of interest which may be described as utilitarian, scientific and aesthetic.

As with the other sciences, astronomy was originally studied for mainly utilitarian reasons. It provided measures of time, and enabled mankind to keep a tally on the flight of the seasons; it taught him to find his way across the trackless desert, and later, across the trackless ocean. In the guise of astrology, it held out hopes of telling him his future. There was nothing intrinsically absurd in this, for even to-day the

astronomer is largely occupied with foretelling the future movements of the heavenly bodies, although not of human affairs—a considerable part of the present book will consist of an attempt to foretell the future, and in so doing to predict the final end, of the material universe. Where the astrologers went wrong was in supposing that terrestrial empires, kings and individuals formed such important items in the scheme of the universe that the motions of the heavenly bodies could be intimately bound up with their fates. As soon as man began to realise, even faintly, the measure of his own insignificance in the universe, astrology died a natural and inevitable death.

The utilitarian aspect of astronomy has by now shrunk to very modest proportions. The national observatories still broadcast the time of day, and help to guide ships across the ocean, but the centre of astronomical interest has shifted so completely that the remotest nebulae arouse incomparably more enthusiasm than "clock-stars," and the average astronomer almost completely neglects our nearest neighbours in space, the planets, and gives his main attention to stars so distant that their light takes hundreds, thousands, or even millions, of years to reach us.

Recently, astronomy has acquired a new scientific interest through establishing its position as an integral part of the general body of science. The various sciences can no longer be treated as distinct; scientific discovery advances along a continuous front which extends unbroken from electrons of a fraction of a millionth of a millionth of an inch in diameter to nebulae whose diameters are measured in hundreds of thousands of millions of millions of miles. A gain of astronomical knowledge may add to our knowledge of physics and chemistry, and *vice versa*. The stars have long ago ceased to be treated as mere points of

light. Each is now regarded as an experiment on a heroic scale, a high-temperature crucible in which nature herself operates through ranges of temperature and pressure utterly beyond any available in our laboratories, and permits us to watch the results. In so doing, we may happen upon properties of matter which have eluded the terrestrial physicist, owing to the small range of physical conditions at his command. For instance matter exists in nebulae with a density at least a million times lower than anything we can approach on earth, and in certain stars at a density nearly a million times greater. How can we expect to understand the whole nature of matter from laboratory experiments in which we can command only one part in a million million of the whole range of density known to nature?

Even more recently, astronomy has become of direct importance to philosophy through the light it has shed on the metaphysical concepts of space and time. It has provided weighty evidence in support of the central doctrine of the theory of relativity—that space and time form a single indissoluble whole. Indeed, whatever may have been the case with the world of professional scientists, it was the results obtained by astronomers at the eclipse of 1919 which first focussed general interest on the theory of relativity, and thus led to our present understanding of the relations between space and time. The even more recent evidence as to the possible expansion of space itself may be found to contain a new and still more profound message as to the meaning of our fundamental metaphysical concepts.

Yet for each one who feels the scientific or philosophical appeal of astronomy, there are probably a dozen who are attracted by its aesthetic appeal. Many even of those who seek after knowledge for its own

sake, driven by that intellectual curiosity which provides the fundamental distinction between themselves and the beasts, find their main interest in astronomy, as being the most poetical and the most aesthetically gratifying of the sciences. They want to exercise their faculties and imaginations on something remote from everyday trivialities, to find an occasional respite from "the long littleness of life," and they satisfy their desires in contemplating the serene immensities of the outer universe. To many, astronomy provides something of the vision without which the people perish.

Before proceeding to describe the results of the modern astronomer's survey of the sky, let us try to envisage in its proper perspective the platform from which his observations are made.

Later on, we shall see how the earth was born out of the sun, something like two thousand millions of years ago. It was born in a form in which we should find it hard to recognise the solid earth of to-day with its seas and rivers, its rich vegetation and overflowing life. Our home in space came into being as a globe of intensely hot gas on which no life of any kind could either gain or retain a foothold.

Gradually this globe of gas cools down, becoming first liquid, then plastic. Finally its outer crust solidifies, rocks and mountains forming a permanent record of the irregularities of its earlier plastic form. Vapours condense into liquids, and rivers and oceans come into being, while the so-called "permanent" gases—oxygen, nitrogen, helium, neon—form an atmosphere. Gradually the earth assumes a condition suited to the advent of life, which finally appears, we know not how, whence or why.

It is not easy to estimate the time since life first appeared on earth, but it can hardly have been more than a small fraction of the whole 2000 million years

of the earth's existence. Still, there was probably life on earth at least 300 million years ago, and possibly as far back as 1000 million years ago. The first life appears to have been wholly aquatic, but gradually fishes changed into reptiles, reptiles into mammals, and finally man emerged from mammals. The evidence favours a period of from 300,000 to 1,000,000 years ago for this last event. Thus life has inhabited the earth for only a fraction of its existence, and man for only a tiny fraction of this fraction. To put it in another way, the astronomical time-scale is incomparably longer than the human time-scale—the generations of man, and even the whole of human existence, are only ticks of the astronomer's clock.

Most of the 10,000 or more generations of men who connect us up with our ape-like ancestry must have lived lives which did not differ greatly from those of their animal predecessors. Hunting, fishing and warfare filled their lives, leaving but little time or opportunity for intellectual contemplation. Then, at last, man began to awake from his long intellectual slumber, and, as civilisation slowly dawned, felt the need for occupations other than the mere feeding and clothing of his body. He began to discover revelations of infinite beauty in the grace of the human form or the play of light on the myriad-smiling sea, which he tried to perpetuate in carefully chiselled marble or exquisitely chosen words. He began to experiment with metals and herbs, and with the effects of fire and water. He began to notice, and try to understand, the motions of the heavenly bodies, for to those who could read the writing in the sky, the nightly rising and setting of the stars and planets provided evidence that beyond the confines of the earth lay an unknown universe built on a far grander scale.

In this way the arts and sciences came to earth,

bringing astronomy with them. We cannot quite say when, but compared even with the age of the human race, *they came but yesterday, while in comparison with the whole age of the earth, their age is but a twinkling of the eye.*

Scientific astronomy, as distinguished from mere star-gazing, can hardly claim an age of more than 3000 years. It is less time than this since Pythagoras, Aristarchus and others explained to a little-heeding and mainly incredulous world that the earth moved around a fixed sun. Yet the really significant figure for our present purpose is not so much the time since men began to make conjectures about the structure of the universe, as the time since they began to unravel its true structure by the help of ascertained fact. The important length of time is that which has elapsed since that evening in 1610 when Galileo first turned his telescope on to Jupiter—a mere three centuries or so.

We begin to grasp the true significance of these round-number estimates when we re-write them in tabular form. We have:

Age of earth	about	2,000,000,000	years
Age of life on earth ...	more than	300,000,000	,,
Age of man on earth ...	more than	300,000	,,
Age of astronomical science	about	3,000	,,
Age of telescopic astronomy	,,	300	,,

When the various figures are displayed in this form we see what a very recent phenomenon astronomy is. Its total age is less than a hundredth part of the age of man, less than a hundred-thousandth part of the time that life has inhabited the earth. During more than 99,999 parts out of the 100,000 of its existence, life on earth was hardly concerned about anything beyond the earth. But whereas the past of astronomy is to be measured on the human time-scale, a hundred generations or so of men, there is every reason to expect that

its future will be measured on the astronomical time-scale. We shall discuss the probable future stretching before the human race in a later chapter. For the moment it is not unreasonable to suppose that this future will probably be terminated by astronomical causes, so that its length is to be measured on the astronomical time-scale. As the earth has already existed for 2000 million years, it is *à priori* reasonable to suppose that it will exist for at least something of the order of 2000 million years yet to come, and humanity and astronomy with it. Actually we shall find reasons for expecting it to last far longer than this. But if once it is conceded that its future life is to be estimated on the astronomical time-scale, no matter in what exact way, we see that astronomy is still at the very opening of its existence. This is why its message can claim no finality—we are not describing the mature convictions of a man, so much as the first impressions of a new-born babe which is just opening its eyes. Even so they are better than the idle introspective dreamings in which it indulged before it had learned to look around itself and away from itself.

And so we set out to learn what astronomy has to tell us about the universe in which we live our lives. Our inquiry will not be entirely limited to this one science. We shall call upon other sciences, physics, chemistry and geology, as well as the more closely allied sciences of astrophysics and cosmogony, to give help, when they can, in interpreting the message of observational astronomy. The information we shall obtain will be fragmentary. If it must be compared to anything, let it be to the pieces of a jig-saw puzzle. Could we get hold of all the pieces, they would, we are confident, form a single complete consistent picture, but many of them are still missing. It is too much to hope that the incomplete series of pieces we have

already found will disclose the whole picture, but we may at least collect them together, arrange them in some sort of methodical order, fit together pieces which are obviously contiguous, and perhaps hazard a guess as to what the finished picture will prove to be when all its pieces have been found and finally fitted together.

CHAPTER I

Exploring the Sky

We have seen how man, after inhabiting the earth for 300,000 years or more, has within the last 300 years—the last one-thousandth part of his life on earth—become possessed of an optical means of studying the outer universe. In the present chapter we shall try to describe the first impressions he has formed with his newly-awakened eyes. The description will be arranged in a very rough chronological order. This is also an order of increasing telescopic power, or again of seeing farther and farther into space, so that our order of arrangement might equally be described as one of increasing distance from the sun. We shall not attempt any sort of continuous record, but shall merely mention a few landmarks so as to shew in broad outline the order in which territory was won and consolidated in man's survey of the universe.

THE SOLAR SYSTEM

We may conveniently start with the solar system, the structure of which was unravelled by Galileo and his successors.

The sun's family of planets falls naturally into distinct groups. Near to the sun are the four small planets, Mercury, Venus, the Earth and Mars. At much greater distances are the four great planets, Jupiter, Saturn, Uranus and Neptune. Beyond all these lies the recently discovered planet Pluto, the outermost member of our system so far known.

Mercury is nearest of all to the sun; next comes Venus. The orbits of these two planets lie between the earth's orbit and the sun. As seen from the earth, these

planets appear to describe relatively small circles round the sun, so that they necessarily appear near to the sun in the sky. As a consequence, they can only be seen either in the early morning, if they happen to rise just before the sun, or in the evening if they set after the sun. The ancients, not altogether recognising that the same planets could appear both as morning and evening stars, gave them different names according as they figured as the one or the other. As a morning star Venus was called Phosphoros by the Greeks and Lucifer by the Romans; as an evening star it was called Hesperus by both.

Next beyond the earth, as we proceed outward from the sun into space, comes Mars, completing the group of small planets. Mars, Venus and Mercury are all smaller than the earth in size, although Venus is only slightly so.

There is a wide gap between the orbit of Mars, the last of the small planets, and that of Jupiter, the first of the great planets. This is not empty; it is occupied by the orbits of thousands of tiny planets known as asteroids. None of these approaches the earth in size; Ceres, the largest, is less than 500 miles in diameter, and only four are known with diameters of more than 100 miles. The planets Mercury, Venus and Mars have all been known from remote antiquity, but the asteroids only entered astronomy with the nineteenth century, Ceres, the first and largest, having been discovered by Piazzi on January 1, 1801.

Beyond the asteroids come the four great planets Jupiter, Saturn, Uranus and Neptune, all of which are far larger than the earth. Jupiter, the largest, is nearly 90,000 miles in diameter. This is more than eleven times the diameter of the earth; fourteen hundred bodies of the size of the earth could be packed inside Jupiter, and leave room to spare. Saturn, which comes

next in order, is second only to Jupiter in size, having a diameter of about 70,000 miles. These two are by far the largest of the planets.

Uranus and Neptune have each about four times the diameter, and so about sixty-four times the volume, of the earth. The size of Pluto is not yet known with accuracy, but present indications are that it contains less substance than the earth, and so is probably of smaller size than the earth.

Jupiter and Saturn form such conspicuous objects in the sky that they have been known from the earliest times, but Uranus and Neptune are comparatively recent discoveries. Sir William Herschel discovered Uranus quite accidentally in 1781, while looking through his telescope with no motive other than the hope of finding something interesting in the sky. By contrast, Neptune was discovered in 1846 as the result of intricate mathematical calculations, which many at the time regarded as the greatest triumph of the human mind, at any rate since the time of Newton. It was a triumph of youth. The honour must be apportioned in approximately equal shares between an Englishman, John Couch Adams, then only 27 years old, who was afterwards Professor of Astronomy at Cambridge, and a young French astronomer, Urbain J. J. Leverrier, who was only eight years his senior. Both attributed certain vagaries in the observed motion of Uranus to the gravitational pull of an exterior planet, and both set to work to calculate the orbit in which this supposed outer planet must move to explain these vagaries.

Adams finished his calculations first, and informed observers at Cambridge as to the part of the sky in which the new planet ought to lie. As a result, Neptune was observed twice, although without being immediately identified as the wanted planet. Before this identification had been established at Cambridge,

Leverrier had finished his computations and communicated his results to Galle, an assistant at Berlin, *who was able to identify the planet at once, Berlin possessing better star-charts of the region of the sky in question than were accessible at Cambridge.*

Gradually it emerged that the gravitational pull of Neptune was inadequate to account for all the vagaries in the motions of Uranus, while similar vagaries began to appear in Neptune's own motion. This pointed to the existence of yet another planet, further out even than Neptune. Just as Adams and Leverrier had done on the former occasion, so Dr Percival Lowell, of Flagstaff Observatory, Arizona, computed the orbit in which the conjectured new planet ought to move, but many years of careful search were necessary before the Flagstaff observers discovered, in March 1930, the planet to which they subsequently gave the name of Pluto. It was found to be moving in almost precisely the orbit which Lowell had predicted fifteen years previously. On the other hand, Lowell's calculations had suggested that the unknown planet ought to be something like eight or ten times as massive as the new planet seems likely to be. For this and other reasons, certain astronomers are inclined to think that the agreement between Lowell's predictions and the actual orbit of Pluto was largely accidental.

As far back as 1772, Bode had pointed out a simple numerical relation connecting the distances at which the various planets moved round the sun. This is obtained as follows: Write first the series of numbers

0	1	2	4	8	16	32	64	128	256

in which each number after the first two is double the preceding. Multiply each by three, thus obtaining

0	3	6	12	24	48	96	192	384	768

and add four to each, giving

4	7	10	16	28	52	100	196	388	772

These numbers are very approximately proportional to the actual distances of the planets from the *sun, which are (taking the earth's distance to be 10):*

3·9	*7·2*	*10·0*	*15·2*	*26·5*	*52·0*	*95·4*	*191·9*	*300·7*	*396*
Mercury	Venus	Earth	Mars	Asteroids	Jupiter	Saturn	Uranus	Neptune	Pluto

The law was enunciated before Uranus and the asteroids had been discovered, so that it is somewhat remarkable that these fit so well into their predicted places. On the other hand, the law fails completely for Neptune and the newly discovered Pluto, so that it seems more than likely that it is a mere coincidence with no underlying rational explanation.

As compared with the earth's distance from the sun, the distances of the outermost planets are enormous. Each square yard of Pluto receives, in round numbers, only a sixteen-hundredth part as much light and heat from the sun as a square yard of the earth receives. It can be calculated from this that if Pluto's surface were warmed only by the heat of the sun, it would be at a very low temperature indeed, somewhere in the neighbourhood of – 230° Centigrade, or more than 400 degrees of frost on the Fahrenheit scale. The corresponding temperature for Neptune and Uranus are only a few degrees higher; for Saturn it is about – 180° Centigrade and for Jupiter about – 150° Centigrade.

A telescope collects heat as well as light. Not only is the heat-gathering power of a large telescope tremendous, but extremely sensitive instruments have been designed to measure this heat. The 100-inch telescope at Mount Wilson is said to be capable of detecting the heat received from a single candle on the banks of the Mississippi, 2000 miles away. This great sensitiveness has made it possible to measure the

infinitesimal amounts of heat received from single stars and planets, and so to estimate the temperatures of their surfaces.

It is found that the surface of Jupiter is at a temperature of about $-150°$ Centigrade, which is just about that at which it would be maintained by the sun's heat alone. On the other hand, similar measurements assign temperatures of $-150°$ and $-170°$ respectively to Saturn and Uranus, both of which are rather higher than would be expected if these planets had no source of heat beyond the sun's radiation. But it seems clear that any sources of internal heat must be quite small, and that all the major planets are very cold indeed. There can be neither seas nor rivers on their surfaces, since all water must be frozen into ice; neither can there be rain or water-vapour in their atmospheres. It has been suggested that the clouds which obscure our view of Jupiter's surface may consist of condensed particles of carbon-dioxide, or some other gas which boils at temperatures far below the freezing point of water.

When we come to the small planets nearer the sun, we meet physical conditions much more like those with which we are familiar on earth. Owing to its greater distance from the sun, Mars is somewhat, but not enormously, colder than the earth. Its day of 24 hours 37 minutes is only slightly longer than our own, so that its surface must experience alternations of warmth by day and cold by night similar to those we find on earth. In the equatorial regions the temperature rises well above the freezing point at noon, occasionally reaching 50° Fahrenheit or even more. But even here it falls below freezing some time before sunset, and from then until well on in the next day, the climate must be very cold. The polar regions are of course colder still, the temperature of the snowcap which covers the poles

being somewhere about – 70° Centigrade or – 94° Fahrenheit—126 degrees of frost!

Venus, being nearer the sun, must have a higher average temperature than the earth. But as each of its days and nights is several days of our terrestrial time, the difference between the temperatures of day and night must be far greater than with us, so that its surface must experience great extremes of heat by day and of cold by night. The night temperature appears to be fairly uniformly equal to about – 25° Centigrade or – 13° Fahrenheit. At any point on the planet's surface weeks of this bitterly cold night temperature must alternate with weeks of a roasting day temperature. It is even possible that Venus always turns the same face to the sun, just as the moon does to the earth; if so, one face of the planet must be perpetually frozen and dark while the other is continually lighted about twice as brightly as our earth is by day, and so must be proportionately hotter.

Mercury is so near the sun that its average temperature is necessarily far higher than that of the earth. It reflects only a tiny fraction—about a fourteenth—of the light and heat it receives from the sun. All the rest goes to heating up its surface. It seems fairly certain that this planet always turns the same face to the sun, in which case the unwarmed half of its surface must be intensely cold, and the warmed half intensely hot. If so, calculation shews that the warmed hemisphere ought to have a temperature of about 357° Centigrade; if however the planet was in fairly rapid rotation, its whole surface would have a temperature of only about 170° Centigrade. Quite recently Pettit and Nicholson have measured the amount of heat received on earth from the warmed hemisphere, and estimate its temperature at about 350° Centigrade or 662° Fahrenheit, thus confirming that the planet always turns the same

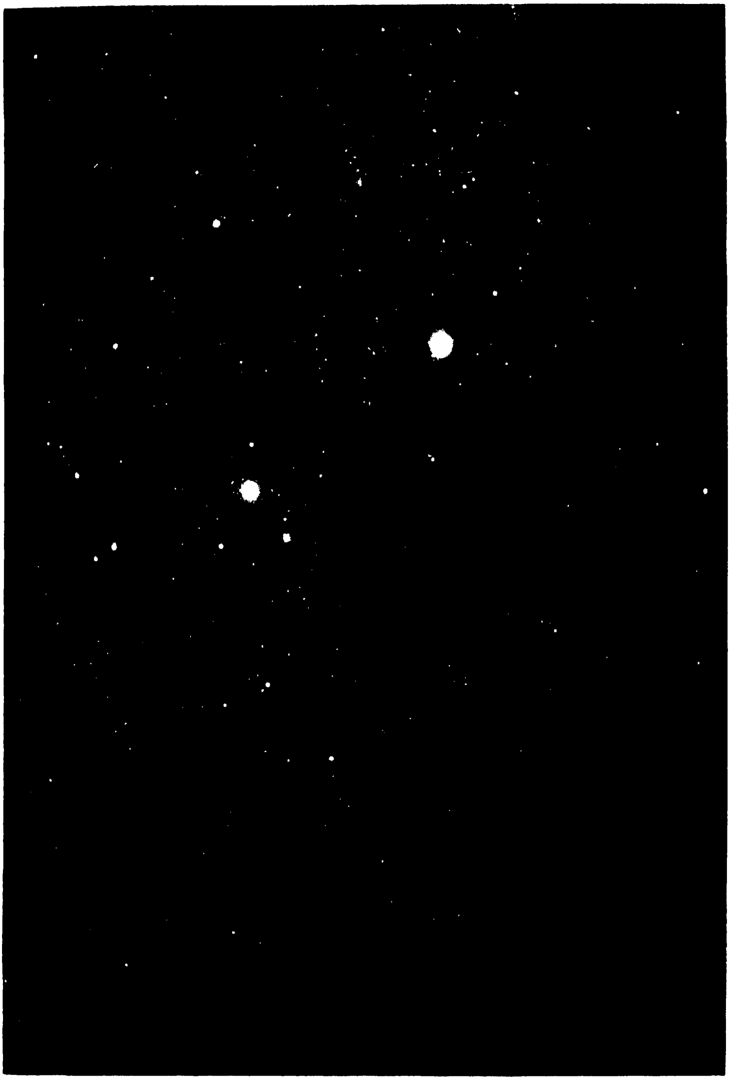
face to the sun. Its warm hemisphere is at a temperature which melts lead; the other hemisphere, eternally dark and unwarmed, may well be colder than anything we ever experience on earth.

Galileo's discovery of the four satellites of Jupiter in 1610 was followed in time by the discovery of further satellites moving round all the planets except the extreme members of the Solar System, namely the two small planets Mercury and Venus which lie nearest the sun and the small planet Pluto which lies farthest away from the sun. In 1655 Huyghens discovered Titan, the largest of Saturn's satellites, and by 1684 Cassini had discovered four more. Then, after the lapse of a full century, Sir William Herschel discovered two satellites of Uranus in 1787 and two more satellites of Saturn in 1789. We shall discuss the full system of planetary satellites and also the smaller bodies of the solar system—comets, meteors and shooting-stars—in a later chapter, when we come to deal with the way they came into being.

THE GALACTIC SYSTEM

Our next landmark is the survey of the stars by the two Herschels, Sir William Herschel, the father (1738–1822) and Sir John Herschel, the son (1792–1871). What Galileo had done for the solar system, the two Herschels set out to do for the huge family of stars—the "galactic" system, bounded by the Milky Way—of which our sun is a member.

On a clear moonless night the Milky Way is seen to stretch, like a great arch of faint light, from horizon to horizon. Travellers find that what we see is only part of a full circle of light—the galactic circle—which stretches completely round the earth and divides the sky into two equal halves. It thus forms a sort of



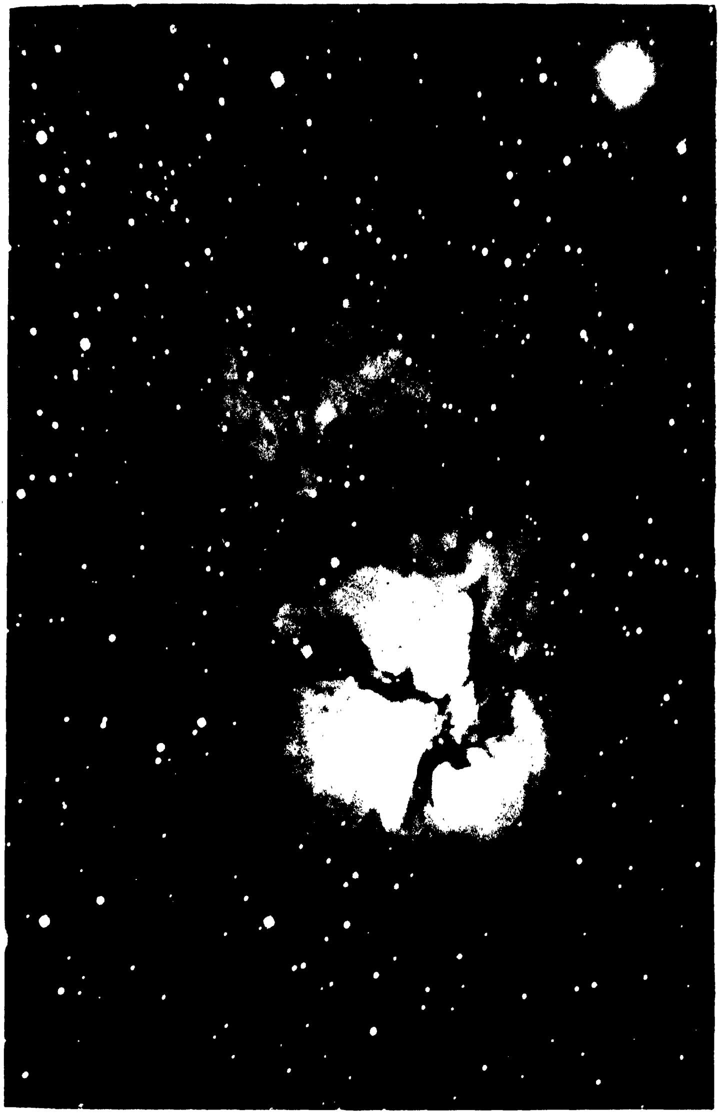
Franklin-Adams Chart

The Milky Way in the neighbourhood of the Southern Cross

PLATE II

E. E. Barnard

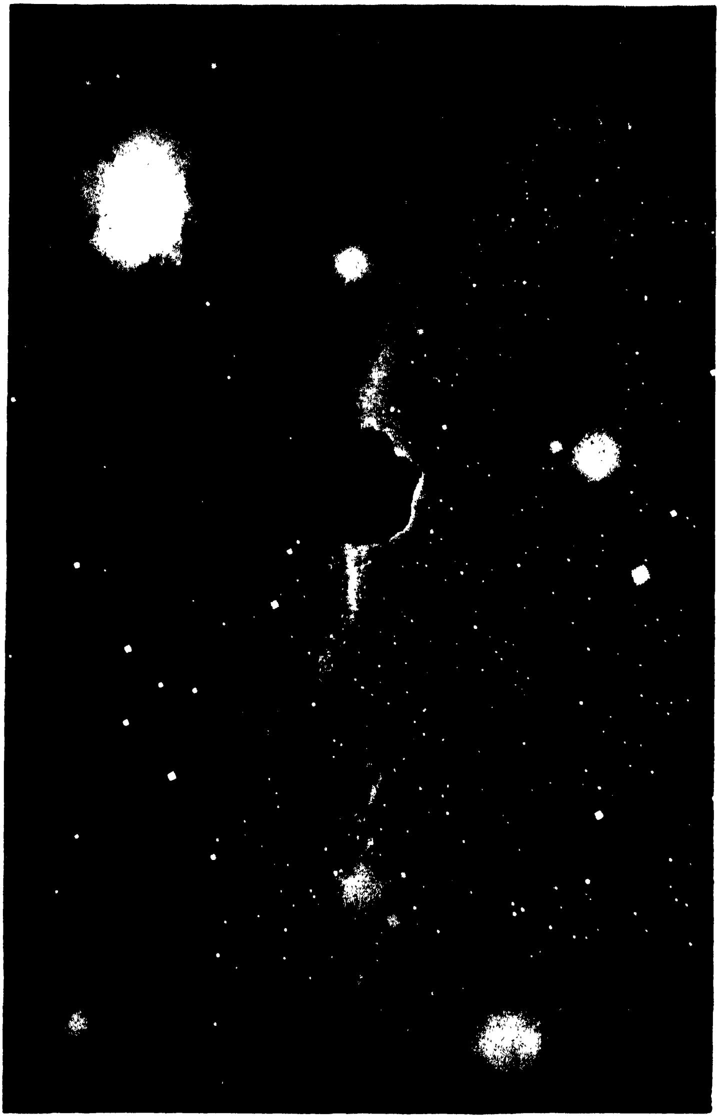
The Milky Way in the region of ρ Ophiuchi



Mt Wilson Observatory

The Trifid Nebula *M* 20 in Sagittarius

PLATE IV



Mt Wilson Observatory

The "Horse's Head" in the Great Nebula in Orion

celestial "equator," with reference to which astronomers are accustomed to measure latitude and longitude in the sky. As Galileo's telescope first shewed, it consists of a crowd of faint stars, each too dim to be seen individually without telescopic aid (see Plates I and II). And, as might be expected, the proper interpretation of this great belt of faint stars has proved to be fundamental to a proper understanding of the architecture of the universe.

If stars were scattered uniformly through infinite space, we should at last come to a star in whatever direction we looked, so that the sky would appear as a uniform blaze of intolerable light. It is true that this would not be the case if light were dimmed or blotted out after travelling a certain distance, but even then, the sky would appear the same in all directions, for there would be no reason why one part of the sky should be more lavishly spangled with stars than another. Thus the existence of the Milky Way shews that the system of the stars does not extend uniformly to infinity. The system must have a definite structure, and it was the architecture of this structure that Sir William Herschel set himself to unravel. The work he did for the northern half of the sky was subsequently extended to the southern hemisphere by his son, Sir John Herschel.

We shall best understand the method employed by the Herschels if we first imagine all the stars in the sky to be intrinsically similar objects. Each would then emit the same amount of light, so that the nearer stars would appear bright, and the farther stars faint, merely as an effect of distance. The way in which apparent brightness decreases with distance is of course well known; the law is that of the "inverse square of the distance," which means that the apparent brightness decreases just as rapidly as the square of its

distance increases; a star which is twice as distant as a second similar star appears only a quarter as bright, and so on. Thus if all stars emitted the same amount of light, we could estimate the relative distances of any two stars in the sky from their relative brightnesses. By calculating the relative distances of various stars, cutting wires proportional to these lengths, and pointing them in the directions of the stars to which they referred, we could form a model of the arrangement of the stars in the sky. We should, in fact, know the whole structure of the system of stars except for its scale. To represent the faint stars of the Milky Way, a great number of very long wires would be needed. In the model these would all point towards different parts of the Milky Way, forming a flat wheel-like structure.

The problem which confronted Sir William Herschel was more intricate than this, because he knew that the stars were of different intrinsic brightness as well as at different distances, and both factors combined to produce differences of apparent brightness. One of the main difficulties of astronomy, both to the Herschels and to the astronomer of to-day, lies in the fact that these two factors have to be disentangled before any definite conclusions can be reached.

Herschel found that the number of stars visible in his telescope-field varied enormously with different directions in space. It was of course greatest when the telescope was pointed at the Milky Way, and fell off, steadily and rapidly, as the telescope was moved away from the Milky Way. Generally speaking, two telescope-fields which were at equal distances from the Milky Way contained about the same number of stars. In the technical language of astronomy, the richness of the star-field depended mainly on the galactic latitude—just as the earth's climate depends mainly on

the geographic latitude—and not to any great extent on the longitude.

Fields at different distances from the Milky Way were found to differ in quality as well as in number of stars. The brightest stars of all occurred about equally in all fields; the observed difference in the fields resulted in the main from faint stars, and particularly the faintest stars of all, becoming enormously more abundant as the Milky Way was approached.

Sir William Herschel rightly interpreted this as shewing that the system of stars surrounding the sun began to thin out within distances reached by his telescope, and that it began to thin out soonest in directions farthest away from the Milky Way. He supposed the general shape of the galactic system of stars to be that of a bun or a biscuit or a watch, the stars being most thickly scattered near the centre, and occurring more sparsely in the outer regions. The plane of the Milky Way of course formed the central plane of the structure. The fact that the Milky Way divides the sky into two almost exactly equal parts suggested to him that the sun must be very nearly in this central plane, and this is confirmed by the recent very refined investigations of Seares and van Rhijn, and others. From the fact that parts of the sky which were equidistant from the Milky Way appeared about equally bright, Herschel inferred that the sun not only lay in the central plane of the system, but was very near to its actual centre, a view which is now known to be untenable (see p. 72 below).

Fig. 1 shews a cross-section of the general kind of structure which Sir William Herschel assigned to the galactic system, although the detailed distribution of stars shewn in the diagram is that given at a much later date (1922) by Kapteyn. It is easy to see how a structure of this type would account for the general

appearance of the sky. Those stars which appear brightest of all are, generally speaking, the nearest; they are so near that no appreciable thinning out of stars occurs within this distance. For this reason the very bright stars occur in about equal numbers in all directions. The stars which appear very faint are mostly very distant, so distant that the great depth of the system in directions in or near to the galactic plane is brought into play. In such directions, layer after layer of stars, ranged almost endlessly one behind the other, give rise to the apparent concentration of faint stars which we call the Milky Way.

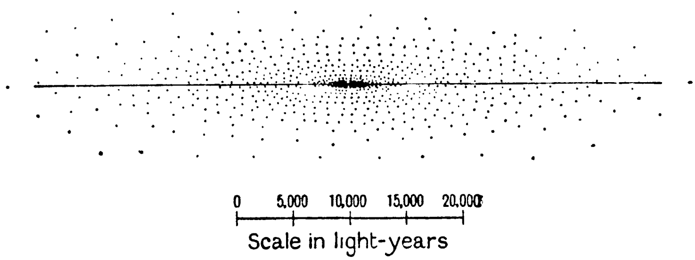


Fig. 1. The structure of the Galactic System according to Herschel and Kapteyn.

This view of the structure of the galactic system prevailed until quite recently. The researches of Shapley and others, which we shall discuss below (p. 70), now shew that it needs amendment in that the sun is no longer believed to be at or near the centre of the system. In other respects it stands as providing a first approximation, at least, to the truth.

The final acceptance of the Copernican view of the structure of the solar system was in a large measure due to Galileo's discovery of the similar system of Jupiter, which happened to be so situated in space that a terrestrial observer could obtain a bird's-eye view of

it as a whole. We can never obtain a bird's-eye view of the solar system as a whole because we can only see it from inside, so that visual confirmation that such systems could exist was only to be obtained through the discovery of other similar systems, which we could see from outside.

Sir William Herschel believed he had obtained visual confirmation of his own view of the structure of the galactic system in the same way, by discovering similar systems, of which he could obtain a bird's-eye view because they were entirely extraneous to the galaxy. These objects were of hazy, nebulous appearance; Herschel spoke of them as "island universes" and believed them to be clouds of stars. He found it impossible to distinguish the separate stars in them, but believed that sufficient telescopic power would make this possible, just as it had enabled Galileo to see the stars in the Milky Way. Actually the separate stars can now be seen (cf. Plate XIV, p. 77, below).

These objects, which we shall describe almost immediately, are generally known as "extra-galactic nebulae" from their position outside and entirely detached from the galactic system, although we shall frequently find it convenient to use the briefer term "great nebulae," to which their immense size fully entitles them.

NEBULAE

A telescope exhibits a planet as a disc of appreciable size, and an eye-piece which magnifies 60 times will make Jupiter look as large as the moon. Yet an eye-piece which magnifies 60 times, or any greater number of times, can never make a star look as large as Jupiter. No magnification within our command causes any star to appear as anything other than a mere point of light. The stars are of course enormously larger than Jupiter,

but they are also enormously more distant, and it is the distance that wins.

The telescope nevertheless shews a number of objects which appear bigger than mere points of light. They are generally of a faint, hazy appearance, and so have received the general name of "nebulae." Detailed investigation has shewn that these fall into three distinct classes.

PLANETARY NEBULAE. The first class are generally described as "Planetary Nebulae." There is nothing of a planetary nature about them beyond the fact that, like the planets, they appear as discs of distinct size, and not as mere points, in a telescope. Only a few hundreds of these objects are known; four typical examples are illustrated in Plate V. They prove to be comparatively faint and near objects, at any rate in comparison with other nebulae we shall be discussing. Van Maanen estimated that 21 which he studied are at an average distance of about 4500 light-years*, and that on the average they give out about ten times as much light as the sun.

We shall discuss their physical structure below (p. 299). For the moment, it is enough to say that they are probably of the nature of stars which have in some way become surrounded by luminous atmospheres of enormous extent. If so, they of course disprove our general statement that no star ever appears as anything but a point of light in a telescope; we must make an exception in favour of the planetary nebulae.

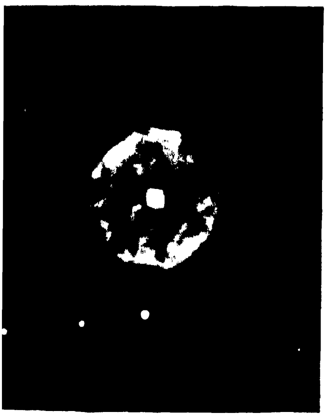
GALACTIC NEBULAE. The second class are generally described as "Galactic Nebulae," examples being shewn in Plates III, IV and VI (pp. 25 and 31). These are completely irregular in shape. Their general appear-

* Light travels at a speed of 186,000 miles a second, and a "light-year" is the distance it travels in a year—approximately six million million miles.

PLATE V

N.G.C. 2022

N.G.C. 6720



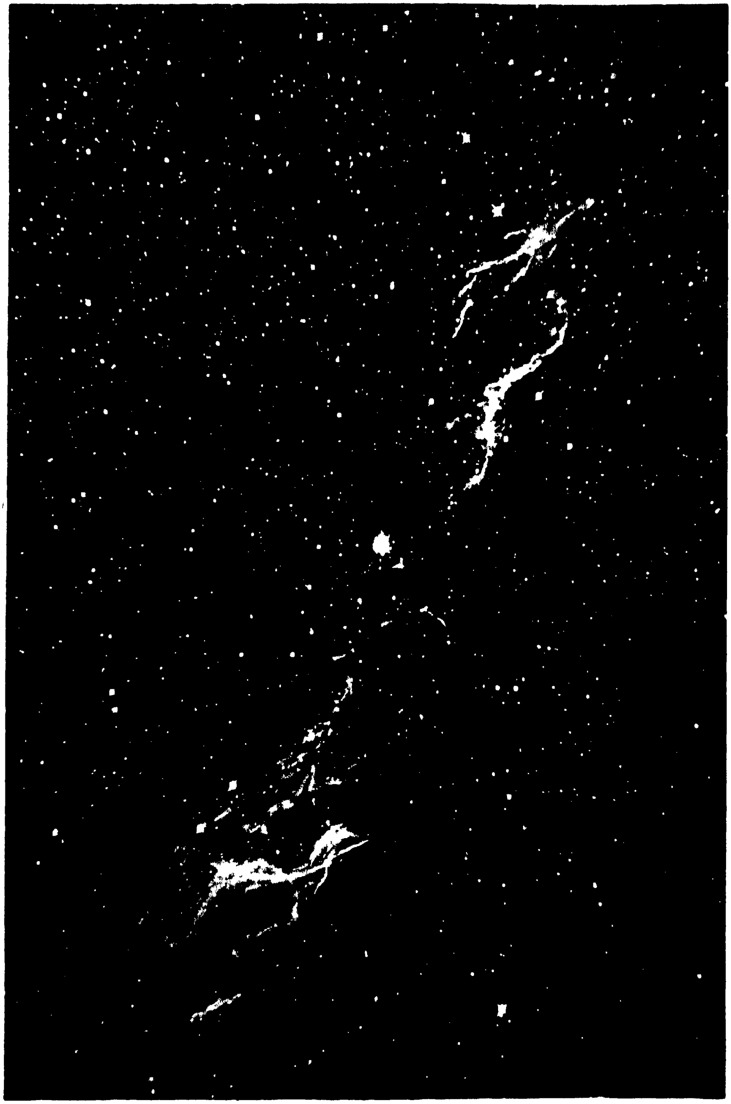
N.G.C. 1501

N.G.C. 7662

Mt Wilson Observatory

Planetary Nebulae

PLATE VI



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The Nebula in Cygnus

ance is that of huge glowing wisps of gas stretching from star to star, and in effect this is pretty much what they are. Like the planetary nebulae, they lie entirely within the galactic system. Even a cursory glance shews that each irregular nebula contains several stars enmeshed with it; careful telescopic examination often extends the dimensions of the nebula almost indefinitely, so that we may have the whole of a constellation wrapped up in a single nebula.

There is but little doubt as to the physical nature of these nebulae. The space between the stars is not utterly void of matter, but is occupied by a thin cloud of gas of a tenuity which is generally almost beyond description. Here and there this cloud may be denser than usual; here and there again it may be lighted up and made to incandesce by the radiation of the stars within it, and may either reflect the light of these stars, or be raised to incandescence and so emit its own light. We know that this is the true origin of the light of these nebulae, for their light reproduces the character of the light of the stars in the nebulae. For instance, the well-known group of the Pleiades is found to be embedded in a vast faintly luminous nebula, whose light provides "a true copy of the light of the star Merope and of the other bright stars of the Pleiades."

In other places the nebula may be entirely opaque to light, lying like a black curtain across the sky. The variations of density, opacity and luminosity in combination produce all the fantastic shapes and varied degrees of light and shade we see in the galactic nebulae.

A similar opacity is responsible for the dark patches which occur in the general arrangement of the stars. A conspicuous example occurs in the part of the Milky Way shewn in Plate I (p. 24); the dark patch which looks at first like a hole in the system of stars, is

graphically described as "The Coal Sack." Other and similar dark patches can be seen in Plates II, III and IV (pp. 24, 25), and also on Plate XI (p. 68). These black patches in the sky cannot possibly represent actual holes, since it is inconceivable that there should be so many empty tunnels through the stars all pointing exactly earthward, so that we are compelled to interpret them as veils of obscuring matter which dim or extinguish the light of the stars behind them.

EXTRA-GALACTIC NEBULAE. The third class of nebula is of an altogether different nature. Its members are for the most part of definite and regular shape, and shew various other characteristics which make them easy of identification. They used to be called "white nebulae" from the quality of the light they emitted. Later Lord Rosse's giant 6-foot telescope revealed that many of them had a spiral structure; these were called "spiral nebulae." The most conspicuous of all the spiral nebulae is the Great Nebula *M* 31 in Andromeda, shewn in Plate VII, which is just, and only just, visible to the naked eye. The astronomer Marius, observing it telescopically in 1612, described it as looking "like a candle-light seen through horn." Plate VIII shews a second example, which is probably of very similar structure but viewed from another angle, so that we see it almost exactly edge-on.

It is now abundantly proved that nebulae of this type all lie outside the galactic system, so that the term "extra-galactic nebulae" provides a suitable name for them. Their size is colossal. Either of the photographs shewn in Plates VII and VIII would have to be enlarged to the size of the whole of Europe before a body of the size of the earth became visible in it, even under a powerful microscope. Their general shape is similar to that which Sir William Herschel assigned to the galactic system, and it was this that originally led

Yerkes Observatory

The Great Nebula *M* 31 in Andromeda

Mt Wilson Observatory

The Nebula N.G.C. 891 in Andromeda seen edge-on

him to regard them as "island universes" similar to the galactic system. We shall see later how far his conjecture has been confirmed by recent research.

THE DISTANCES OF THE STARS

The year 1838 may well provide our next landmark; in this year the distance of a star was first measured.

In the second century after Christ, Ptolemy had argued that if the earth moved in space, its position relative to the surrounding stars must continually change. As the earth swung round the sun, its inhabitants would be in the position of a child in a swing. And, just as the swinging child sees the nearer trees, persons and houses oscillating rhythmically against a remote background of distant hills and clouds, so the inhabitants of the earth ought to see the nearer stars continually changing their position against their background of more distant stars. Yet night after night the constellations remained the same, or so at least Ptolemy believed; the same stars circled eternally in the same relative positions around the pole, and conspicuous groups of stars such as the seven stars of the Great Bear, the Pleiades or the constellation of Orion shewed no signs of change. For aught the unaided human eye could tell, the stars might be spots of luminous paint on a canvas background, with the earth forming an unmoving pivot around which the whole structure swung.

In opposition to this, the Copernican theory of course required that the nearer stars should be seen to move against the background of the more distant stars, as the earth performed its yearly journey round the sun. Yet year after year, and even century after century, passed without any such motion being detected. The old Ptolemaic contention that the earth formed

the fixed centre of the universe might almost have regained its former position, had it not been that various lines of evidence had begun to shew that even the nearest stars were necessarily very distant—so distant, indeed, that their apparent want of motion need cause no surprise. The child in a swing cannot expect to have optical evidence of its own motion if the nearest object it can see is twenty miles away.

For instance, very few stars appear brighter than Saturn at its brightest; it looks about as bright as Altair, the eleventh brightest star in the sky. Yet Saturn shines only by the light it reflects from the sun, and its distance from the sun is such that it receives only about one part in 2500 million of the total light emitted by the sun. And, as the surface of Saturn only reflects back about two-fifths of the light it receives, it follows that Saturn shines with only a 6000 millionth part of the total light emitted by the sun. If, as Kepler and others had maintained, Altair was essentially similar to the sun, it would probably be of about the same candle-power as the sun, and so would give out about 6000 million times as much light as Saturn. The fact that Altair and Saturn appear about equally bright in the sky can only mean that Altair is 80,000 times as distant as Saturn*. This argument is essentially identical with one which Newton gave in his *System of the World* to shew that even the brightest stars, such as Altair, must be very distant indeed.

And such has proved to be the case. All efforts to discover the apparent swinging motion of the stars—"parallactic motion," as it is technically called—which results from the earth's orbital motion failed until 1838, when three astronomers, Bessel, Henderson, and

* For the apparent brightness of an object falls off as the inverse square of its distance, and the square of 80,000 is approximately equal to 6000 million.

Struve, almost simultaneously detected the parallactic motions of the three stars, 61 Cygni, α Centauri and α Lyrae respectively. The amount of the parallactic motions of these stars made it possible to calculate their distances. In this way, the inhabitants of the earth were not only placed in possession of definite ocular proof that they were swinging round the sun, but from the visible effects of this swing they were able to compute the distances of the nearer stars. The calculated values were not accurate when judged by modern standards, but they provided the first definite estimates of the scale on which the universe is built.

Let us pause for a minute to consider how this scale is built up. The first step is to select a convenient base-line a few miles in length on the surface of the earth, and to measure this in terms of standard yards or metres. Starting out from this base-line, a geodetic survey maps out a long narrow strip of the earth's surface, preferably running due north and south. The difference of latitude at the two ends is then measured by astronomical methods, as for instance by noticing the difference in the altitude of the pole-star at the two places. As the length of the strip is already known in miles, this immediately gives the dimensions of the earth.

The method is identical with that used by the earliest Greek geometers. By its use Erotosthenes of Alexandria (*ca.* 276–195 B.C.) estimated the circumference of the earth to be 250,000 stadia, which, on any reasonable conjecture as to the length of the stadion, was fairly near the truth. According to the values adopted by the International Geodetic Association, the earth's equatorial radius is 6378·388 kilometres, or 3963·34 miles, its polar radius being 6356·912 kilometres or 3949·99 miles.

Having determined the size of the earth, the next

step is to determine the size of the solar system in terms of that of the earth. When the sun is eclipsed by the moon, the time at which the moon first begins to cover the sun's disc is different for different stations on the earth's surface, and the observed differences of time enable us to measure the moon's distance in terms of known distances on the surface of the earth. In this way the mean distance of the moon is found to be 384,403 kilometres or 238,857 miles. In the same way the transit of the planet Venus across the disc of the sun provides an opportunity for determining the scale of the solar system in terms of the dimensions of the earth. The asteroid Eros provides still better opportunities. The Paris Conference (1911) adopted 149,450,000 kilometres, or 92,870,000 miles, as the most likely value for the mean distance of the earth from the sun.

The next and final step is that of using the diameter of the earth's orbit as base-line, and determining the distances of the stars. It was this step which the year 1838 saw accomplished.

The first step in this progression, that from the standard yard or metre to the measured base-line on the earth's surface, involves an increase of several thousand-fold in length. The increase involved in the next step, from the base-line to the earth's diameter, is again one of thousands. And again the next step, from the diameter of the earth to that of the earth's orbit involves an increase of thousands. But the last step of all, from the earth's orbit to stellar distances, is found to involve a million-fold increase.

For recent measurements shew that the nearest stars are almost exactly a million times as distant as the nearest planets. At its nearest approach to the earth, Venus is 26 million miles distant, while the nearest star, Proxima Centauri, is 25,000,000 million miles

away; this latter star is a faint companion of the well-known bright star α Centauri in the southern hemisphere. The distances of the planets when at their nearest, and of the nearest stars, are shewn in the following table:

Planets		Stars		
Name	Distance (miles)	Name	Distance (miles)	Distance (light-years)
Venus	26,000,000	Proxima Centauri	25,000,000 million	4·27
		α Centauri		4·31
Mars	35,000,000	Munich 15040	36,000,000 ,,	6·06
		Wolf 359	47,000,000 ,,	8·07
Mercury	47,000,000	Lalande 21185	49,000,000 ,,	8·33
		Sirius	51,000,000 ,,	8·65

As it is almost impossible to visualise a million, the mere statement that the stars are a million times as remote as the planets gives only a feeble indication of the immensity of the gap that divides the solar system from its nearest neighbours in space. Perhaps the apparent fixity of the stars can be made to convey a more vivid impression of their remoteness.

The earth performs its yearly journey round the sun at a speed of about 18½ miles a second, which is about 1200 times the speed of an express train. The sun moves at nearly the same rate through the group of stars surrounding it—to be precise, at about 800 times the speed of an express train. And, broadly speaking, the nearer planets and the majority of the stars move with similar speeds. We shall not obtain a bad approximation to the truth if we imagine that all astronomical bodies move with exactly equal speeds, let us say, to fix our thoughts, a speed equal to 1000 times the speed of an express train. The distances of astronomical objects are now betrayed by the speed with which they appear to move across the sky—the slower their

apparent motion the greater their distances, and *vice versa*. Now the planets move across the sky so rapidly that it is quite easy to detect their motion from night to night and even from hour to hour; the stars move so slowly that, except with telescopic aid, no motion can be detected from generation to generation, or even from age to age. Even the conspicuous constellations in the sky, which on the whole are formed of the nearest stars of all, have retained their present appearance throughout the whole of historic times. The contrast between the planets which change their positions every hour, and the stars which fail to shew any appreciable change in a century, gives a vivid impression of the extent to which the stars are more distant than the planets.

It is far more difficult to visualise the actual distances of the stars. The statement that even the nearest of them is 25,000,000 million miles away hardly conveys a definite picture to the mind, but we may fare better with the alternative statement that the distance is four and a quarter light-years—the distance that light, travelling at 186,000 miles a second, takes four and a quarter years to traverse.

Light travels with the same speed as wireless signals because both are waves of electric disturbance. Incidentally this speed is just about a million times that of sound. The enormous disparity in the speeds of sound and of electric waves is vividly brought out in the ordinary process of broadcasting. When a speaker broadcasts from London his voice takes longer to travel 3 feet from his mouth to the microphone as a sound wave, than it does to travel a further 500 miles to the north of Scotland as an electric wave. Wireless listeners in Australia hear the music of a concert broadcast from London sooner than an ordinary listener at the back of the London concert hall who relies on sound alone;

they hear it a fifteenth of a second after it is played. Yet these same wireless waves, travelling with the speed of light, take four and a quarter years to reach the nearest star, so that the inhabitants of Proxima Centauri would be over four and a quarter years late in hearing a terrestrial concert. And in time we shall have to consider other and even more distant stars which terrestrial music would not yet have reached had it started on its journey before the Norman Conquest, before the Pyramids were built, even before man appeared on earth.

SPECTRUM ANALYSIS

As our next landmark we may suitably take the application of spectrum analysis to astronomy.

*All light is a blend of lights of different colours, and just as Newton, with his famous prism, analysed sunlight into all the colours of the rainbow, so the spectro*scope analyses the light from a star, or indeed from any source whatever, into its various constituent colours. The instrument spreads out the analysed light into a strip of light of continuously graduated colour, which is described as a "spectrum." In this the colours are the same as in the rainbow, and are found to be arranged in the same order, running from violet through green and orange to red. The reason for this is that the rainbow is itself a "spectrum" of light. Indeed the simplest spectroscope in the world consists of a single globule of water, such as a drop of dew or a drop of rain. A multitude of such globules—a patch of dewy lawn or a shower of rain—forms a better spectroscope, which breaks up the light just as a laboratory spectroscope does.

There is of course a physical reason underlying the invariable sequence of colours. We shall see later

(p. 187) that light consists of trains of waves—like the ripples which the wind blows up on a pond—and that the different colours of light result from waves of different lengths, red light being produced by the longest waves, and violet light by the shortest. The colours in the spectrum occur in the order of their wave-lengths, from the longest (red) to the shortest (violet).

In 1814 Fraunhofer repeated Newton's analysis of sunlight, and found that the spectrum was crossed by a number of dark lines, so that certain short ranges of colour were either deficient or entirely missing from the light of the sun. These lines are still known as the Fraunhofer lines. We shall discuss the physical reason for their existence later (p. 144).

It has since been found that the spectra of all stars are crossed by somewhat similar lines. The exact position of these lines conveys a wealth of information to the astronomer. In favourable cases they may tell him the temperature, density and chemical composition of the atmosphere of a star; the star's distance from us, and the speed with which that distance is increasing or decreasing; and possibly even the weight of the star and the rate at which it is rotating.

THE PHOTOGRAPHIC EPOCH

If we were only allowed to select one more landmark in the progress of astronomy, we might well choose the application of photography to astronomy in the closing years of the nineteenth century; this opened the flood-gates of progress more thoroughly than anything else had done since the invention of the telescope. Hitherto the telescope, after collecting and bending rays of light from the sky, had projected the concentrated beam of light through the pupil of the human eye on

to the retina; in future it was to project it on to the incomparably more sensitive photographic plate. The eye can retain an impression only for a fraction of a second; the photographic plate adds up all the impressions it receives for hours or even days, and records them practically for ever. The eye can only measure distances between astronomical objects by the help of an intricate machinery of cross-wires, screws and verniers; the photographic plate records distances automatically. The eye, betrayed by preconceived ideas, impatience or hope, can and does make every conceivable type of error; the camera cannot lie.

And so it comes about that if we try to pick out landmarks in twentieth-century astronomy we find that, in a sense, it consists of nothing but landmarks; the slow, arduous methods of conquest of the nineteenth century have given place to a sort of gold-rush in which claims are staked out, the surface scratched, the more conspicuous nuggets collected, and the excavation abandoned for something more promising, all with such rapidity that any attempt to describe the position is out of date almost before it can be printed. We can only attempt a general impression of the new territory, and with this will be inextricably mixed a discussion of old territory seen in the light of new knowledge.

GROUPS OF STARS AND BINARY SYSTEMS

A glance at the sky, or, better, at a photograph of a fragment of the sky, suggests that, in the main, the stars are scattered at random over the sky, except for the concentration of faint stars in and towards the Milky Way, which we have already considered. Any small bit of sky does not look very different from what it would if bright and faint stars had been sprinkled haphazard out of a celestial pepperpot.

Yet this is not quite the whole story. Here and there groups of conspicuous stars are to be seen, which can hardly have come together purely by accident. Orion's belt, the Pleiades, Berenice's hair, even the Great Bear itself, do not look like accidents, and in point of fact are not. It is the existence of these natural groups of stars that lies at the root of, and justifies, the division of the stars into constellations. We shall explain later how the physical properties of the stars are studied; for the present it is enough to remark that physical study confirms the suspicion that groups such as those just mentioned are, generally speaking, true families, and not mere accidental concourses, of stars. The stars of any one group, such as the Pleiades, not only shew the same physical properties, but also have identical motions through space, thus journeying perpetually through the sky in one another's society. As the stars of such a group are both physically similar, and travel in company, they might appropriately be described as a family of stars. The astronomer, however, prefers to call them a "moving cluster."

These families are of almost all sizes, the smallest and commonest type consisting of only two members. After this the next commonest type consists of three members; our nearest three neighbours in space, Proxima Centauri and the two stars of α Centauri, form such a triple system. Then come systems of four, five and six members, and so on indefinitely.

Let us first turn our attention to families consisting of only two members—"binary systems," as they are generally called. Even if the stars had been sprinkled on to the sky at random out of a pepperpot, the laws of chance would require that in a certain number of cases pairs of stars should appear very close together. And a study of a photograph of any star-field shews that a large number of such close pairs actually exist.

The number is, however, greater than can be explained by the laws of chance alone. Some pairs of stars may be close together by accident, but a physical cause is needed to account for the remainder. We can unravel the mystery by photographing the field at intervals of a few years and comparing the various results obtained. Some of the stars which originally appeared as close pairs will be found to move steadily apart. These are the pairs of stars which, although they appeared close together in the sky, were not so in space; one star merely happened to be almost exactly in line with the other as seen from the earth. Other pairs are found not to break up with the passage of time; although the two components change their relative positions, they never become completely separated. In the simplest case of all, one star may be found to describe an approximately circular orbit about the other, just as the earth does round the sun, and the moon round the earth, and for precisely the same reason: gravitation keeps them together.

THE LAW OF GRAVITATION. Drop a cricket ball from your hand and it falls to the ground. We say that the cause of its fall is the gravitational pull of the earth. In the same way, a cricket ball thrown into the air does not move on for ever in the direction in which it is thrown; if it did it would leave the earth for good, and voyage off into space. It is saved from this fate by the earth's gravitational pull which drags it gradually down, so that it falls back to earth. The faster we throw it, the farther it travels before this occurs; a similar ball projected from a gun would travel for many miles before being pulled back to earth.

The law governing all these phenomena is quite simple. It is that the earth's gravitational pull causes all bodies to fall 16 feet earthward in a second. This is true of all bodies which are free to fall, no matter

how they are moving; every body which is not in some way held up against gravitation is 16 feet lower at the end of any second than it would have been if gravitation had not acted through that second.

To illustrate what this means, let the big circular curve $B'A'C'$ in fig. 2 represent the earth's surface, and imagine that a shot is fired horizontally from A, the top of an elevation AA'. If the shot were not pulled earthwards by gravitation, it would travel indefinitely along the line AB out into space. If AB is the distance it would travel in a second under these imaginary conditions, the end of a second's actual flight does not find it at B, but at a point 16 feet nearer the earth,

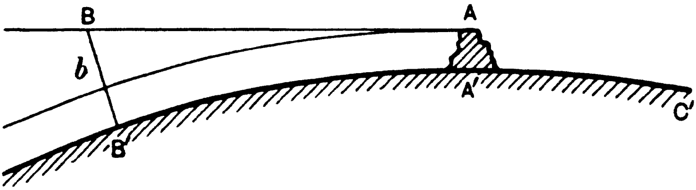


Fig. 2.

gravitation having pulled it down this 16 feet during its flight. For instance, if BB' in fig. 2 should happen to be 16 feet, the shot would strike the earth at B' after a flight of precisely one second.

As another example, let us suppose that the 16-foot fall below B does not drag the shot down to earth but only to a point b, which is at precisely the same height above the earth's surface as the point A at which the shot started. If gravitation were not acting, so that the shot travelled along the line AB, its height above the earth would continually increase. Actually in the case we are now considering, gravitation pulls the shot down at just such a rate as to neutralise the increase of height which would otherwise occur, so that the height of the shot neither increases nor decreases; it

neither flies off into space nor drops to earth, but continues to describe circles round the earth indefinitely.

A simple geometrical calculation shews that for the distance *Bb* to be 16 feet, the distance *AB* travelled in one second must be 25,880 feet or 4·90 miles*. Thus, if we could fire a shot horizontally with a speed of 4·90 miles a second, it would describe endless circles round the earth, the earth's gravitational pull exactly neutralising the natural tendency of the shot to fly away along the straight line *AB*.

In 1665 Newton began to suspect that this same gravitational pull might be the cause of the moon describing a circular orbit around the earth instead of running away at a tangent into space. The moon's distance from the earth's centre is 238,857 miles, or 60·27 times the radius of the earth. As the moon describes a circle of this size every month (27 days 4 hours 43 minutes 11·5 seconds), we can calculate that its speed in its orbit is 2287 miles an hour. After one second it will have travelled 3350 feet, and if it kept to a strictly rectilinear course this would carry it

* Let C be the centre of the earth, and bCD the diameter through b. Then $BA^2 = Bb \times BD$, where $Bb = 16$ feet, and BD, which is 16 feet more than the earth's diameter $= 41{,}900{,}000$ feet. From this we

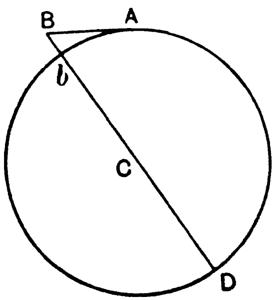


Fig. 8.

readily calculate that $BA = 25{,}880$ feet. This calculation of course neglects the height of the hill AA' by comparison with the earth's diameter.

0·0044 feet farther away from the earth. Thus, to keep in an exact circular orbit around the earth, it must fall 0·0044 feet in a second. This is far less than a body falls in a second at the earth's surface, but Newton conjectured that the force of gravity must weaken as we recede from the earth's surface. Actually a body at the earth's surface falls 3632 times as fast as the moon's earthward fall in its orbit. Now 3632 is the square of 60·27 (or $3632 = 60{\cdot}27 \times 60{\cdot}27$), whence Newton saw that the moon's fall would be of exactly the right amount if the force of gravity fell off as the inverse square of the distance—that is to say, if it decreased just as rapidly as the square of the distance increased. As we shall see later, astronomical observation confirms the truth of this law in innumerable ways. This led Newton to put forward his famous law of gravitation according to which the gravitational pull of any body, such as the earth, falls off inversely as the square of the distance from the body.

Various experimenters have measured the gravitational pull which a few tons of lead exert in the laboratory, and, with this knowledge, it is easy to calculate how many tons the earth must contain so as to exert its observed gravitational pull on bodies outside it. It is found that the earth's weight must be just under six thousand million million million tons*, or, as we shall write it, 6×10^{21} tons†.

* Here, as throughout the book, we use the French or metric ton of a million grammes or 2204·5 lbs. The English ton of 2240 lbs. is equal to 1·0160 French tons.

† The notation 6×10^{21} stands for the number formed by a 6 followed by 21 zeros, this shorthand notation being essential, in the interests of brevity, in discussing astronomical numbers. A million is 10^6, a million million is 10^{12} and so on.

A similar notation is needed to express very small numbers. The expression 10^{-21} is written for $\frac{1}{10^{21}}$ and so on. Thus 6×10^{-6} stands for $\frac{6}{1,000,000}$ or 0·000006.

Just as the earth's gravitational pull keeps the moon perpetually describing circles around it, so the sun's gravitational pull keeps the earth and all the other planets describing circles around the sun. Knowing the distance of any planet from the sun, and also its speed in its orbit, we can calculate the distance this planet falls towards the sun in a second. This tells us the amount of the sun's gravitational pull, and from this we can calculate that the sun's weight must be about 332,000 times the weight of the earth, or almost exactly 2×10^{27} tons. Whichever of the planets we use, we obtain exactly the same weight for the sun. This not only gives us confidence in our result, but incidentally it also provides striking confirmation of the truth of Newton's law of gravitation, for if this law were inexact or untrue, the different planets would not all tell exactly the same story as to the sun's weight. Einstein has recently shewn that the law is not absolutely exact, but the amount of inexactness is inappreciable except for the nearest planet, Mercury, and even here it is so exceedingly small that we need not trouble about it for our present purpose.

Just as we can weigh the sun and earth by studying the motion of a body gripped by their gravitational pull—or "in their gravitational fields," as the mathematician would say—so we can weigh any other body which keeps a second small body moving round it by its gravitational attraction. For instance, the motions of Jupiter's satellites make it possible to weigh Jupiter; its weight is found to be about $1{\cdot}92 \times 10^{24}$ tons, which is 317 times the weight of the earth, although still only $\frac{1}{1047}$ of that of the sun. Similarly the weight of Saturn is found to be $5{\cdot}71 \times 10^{23}$ tons or about $94{\cdot}9$ times that of the earth.

WEIGHING THE STARS. And now we come to a striking application of the principles just explained—

when we observe two stars in the sky describing orbits about one another, we can weigh the stars from a study of their orbits. Generally the problem is not quite so simple as those we have just discussed. For its adequate treatment, we must once again levy toll on the mathematical work of Newton.

We have seen that a projectile fired horizontally with a speed of 4·90 miles a second would describe endless circles round the earth. What would happen if it were fired in some other direction and with some other speed?

The answer was provided by Newton. He shewed that when a small body is allowed to move freely under the gravitational pull of a big body, it will run away altogether if its speed exceeds a certain critical amount, in which case its orbit is the curve called a hyperbola. But if its speed is less than this critical amount, its orbit will always be an ellipse—a sort of pulled out circle or oval curve* (fig. 4, p. 49). Many years before Newton proved this, Kepler had found that the actual paths of the planets round the sun were not exact

* The simplest definition of an ellipse is that it is the curve drawn by a moving point P which moves in such a way that the sum of its distances PS, PT from two fixed points S, T remains always the same. In practice we can most easily draw an ellipse by slipping an endless string $SPTS$ round two drawing pins S, T stuck into a drawing board. Stretch the string tight with a pencil at P, and on letting the pencil move round, keeping the string always tight, we shall draw an ellipse. If the pins S, T in the drawing board are placed near to one another the curve described by the pencil P is nearly circular. The ratio of the distance ST to the length of the remainder of the string $SP + PT$ is called the "eccentricity" of the ellipse; it is necessarily less than unity, because two sides of a triangle are together greater than the third side.

In the limiting case in which the eccentricity is made zero, the ellipse becomes a circle. If the eccentricity is nearly as large as unity, the ellipse is very elongated. All the different shapes of ellipses are obtained by letting the eccentricity change from 0 to 1, and these represent all the different shapes of orbit that a small body can describe around a heavy gravitating mass. The points S, T are called the foci of the ellipse, and the big attracting body always occupies one or other of the two foci of the ellipse.

circles but ellipses; for the most part they were ellipses which did not differ greatly from circles, being what the mathematician calls "ellipses of small eccentricity." Now it can be proved that if the force of gravitation were to fall off in any way other than according to Newton's law of the inverse square of the distance, the orbits of the planets would not be elliptical, so that Kepler's discovery provided confirmation of the truth of Newton's law of gravitation.

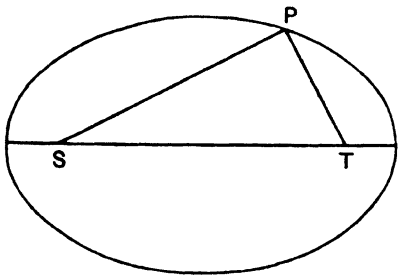


Fig. 4. The oval curve is an ellipse; the points S, T are its "foci."

When the astronomer studies the motions of a binary star in the sky, he again finds that, generally speaking, the two components do not move in circles about one another but in ellipses*. Once again, Newton's law is confirmed, and we are entitled to assume that the forces which keep binary stars together are the same gravitational forces as keep the moon from running away from the earth, or the planets from the sun. Assuming this, a study of these ellipses makes it possible to weigh the stars. If one of the component masses were enormously heavier than the other, the former would stand still while the lighter component

* What he actually observes is the "projection" of the orbit on the sky, but it is a well-known theorem of geometry that the projection of an ellipse is always an ellipse.

described an ellipse around it, the motion being essentially similar to that of a planet around the sun. Such cases are not observed in actual binary stars because the two components are generally comparable in weight, and this brings new complications into the question. There is no need to enter into mathematical details here. Suffice it to say that when neither star stands still, the two components merely describe ellipses of different sizes, and from a study of these two ellipses the weights of both the components can be determined.

The following table shews the result of weighing the four binary systems nearest the sun in this way, the sun's weight being taken as unity:

Stellar Weights

Binary systems near the sun.

Star	Distance in light years from the sun	Weights of components in terms of sun's weight	Luminosity (see p. 51)
α Centauri *A*	4·31	1·14	1·12
,, *B*		0·97	0·32
Sirius *A*	8·65	2·45	26·3
,, *B*		0·85	0·009
Procyon *A*	10·5	1·24	5·5
,, *B*		0·39	0·00006
Kruger 60 *A*	12·7	0·25	0·0026
,, *B*		0·20	0·0007

We see that the weights of these stars do not differ greatly from that of the sun, although naturally the whole of space provides a greater range than the four stars of our table which happen to be near the sun. But even in the whole of space, no star whose weight is known with any accuracy has a weight less than Kruger 60 *B*, although at the other end of the scale there are many stars with far greater weights than any in our table. Of stars whose weights are known with fair accuracy, the star H.D. 1337 (Pearce's star)

is the weightiest, its two components being respectively 36·3 and 33·8 times as heavy as the sun. Plaskett's star B.D. 6° 1309 is certainly heavier still, its components weighing at least 75 and 63 times as much as the sun, and probably more; the exact weights are not known (see p. 61 below). The system 27 Canis Majoris consists of four stars, whose combined weight has been estimated at as much as 2000 times the weight of the sun, but as the evidence is uncertain we may properly exercise a certain amount of caution before accepting a figure so far outside the usual run of stellar weights.

The average constituent star in the above very short table has 0·94 times the weight of the sun, so that this very meagre evidence seems to suggest that our sun is of rather more than average weight, and this is confirmed by a more extensive study of stellar weights.

We might have expected that the stars would prove to have all sorts of weights, for there is no obvious *à priori* reason why stars should not exist with weights millions of times that of the sun, or again with weights only equal to that of the earth or less. Actually we find that the weights of the stars are fairly uniform, very few stars having weights greatly dissimilar from that of the sun. This seems to indicate that a star is a definite species of astronomical product, not a mere random chunk of luminous matter.

LUMINOSITY. The last column of the table on p. 50 gives the "luminosities" of the stars, which means their candle-power as lights, that of the sun being taken as unity. For instance the entry of 26·3 for Sirius means that Sirius, regarded as a lighthouse in space, has 26·3 times the candle-power of the sun. The luminosities of the stars shew an enormously greater range than their weights. In a general way the heaviest stars are found to be the most luminous, as we should naturally expect,

but their luminosity is out of all proportion to their weight. The heavier component of Sirius has only 2·9 times the weight of the lighter component, but 8000 times its luminosity. The system of Procyon is even more remarkable; the heavier component has 8·2 times the weight, but 90,000 times the luminosity, of the lighter component. It appears to be an almost universal law that the candle-power per ton is far greater in heavy stars than in light. This is one of the central and, at first sight, one of the most perplexing facts of physical astronomy: it is so fundamental and so pervading that no view of stellar mechanism can be accepted which fails to explain it.

SPECTROSCOPY

THE COMPOSITION OF THE STARS. When the light from a simple chemical substance, such as sodium or calcium, is broken up spectroscopically, it is not found to give a continuous band of light, but rather a pattern, in which bright and dark places alternate. This pattern is found to be characteristic of the substance, so that an examination of the pattern makes it possible to deduce the nature of the substance emitting the light. It is reported that the two spectroscopists Kirchkoff and Bunsen examined the light from a distant fire in Mannheim through a spectroscope, and, detecting the characteristic pattern of the element strontium in the spectrum of the fire, concluded that there must be strontium in the burning material. It was then a simple step to reason—if we can detect the nature of this distant burning material, why not also that of the material of the sun and stars? Three years later, in 1862, Sir William Huggins had already observed the spectra of about 40 stars, and recognised the known spectral patterns of many known chemical

substances in them. A few years later, the Italian astronomer Secchi had observed about 4000 stellar spectra and classified them into distinct types, which he designated as types I, II, III and IV.

It is now possible to tell the chemical constitution of the atmosphere of a star with considerable accuracy from a study of its spectrum; the composition of the interior layers is of course not accessible to observation. With a few insignificant exceptions, the whole spectral pattern can be identified as arising from substances which are known on earth, so that we may conclude that, as regards their outer layers at least, the stars are built of the same chemical elements as the earth.

Professor H. N. Russell gives the proportion of metallic elements in the sun's atmosphere as follows:

Composition of sun's atmosphere

Metals only: by weight (tons per square mile in visible atmosphere).

Magnesium	850	Manganese	10
Iron	250	Cobalt	6
Silicon	150	Chromium	6
Sodium	100	Titanium	2
Potassium	50	Vanadium	1·5
Calcium	50	Copper	1·5
Aluminium	15	Zinc	1
Nickel	15	All others	0·2

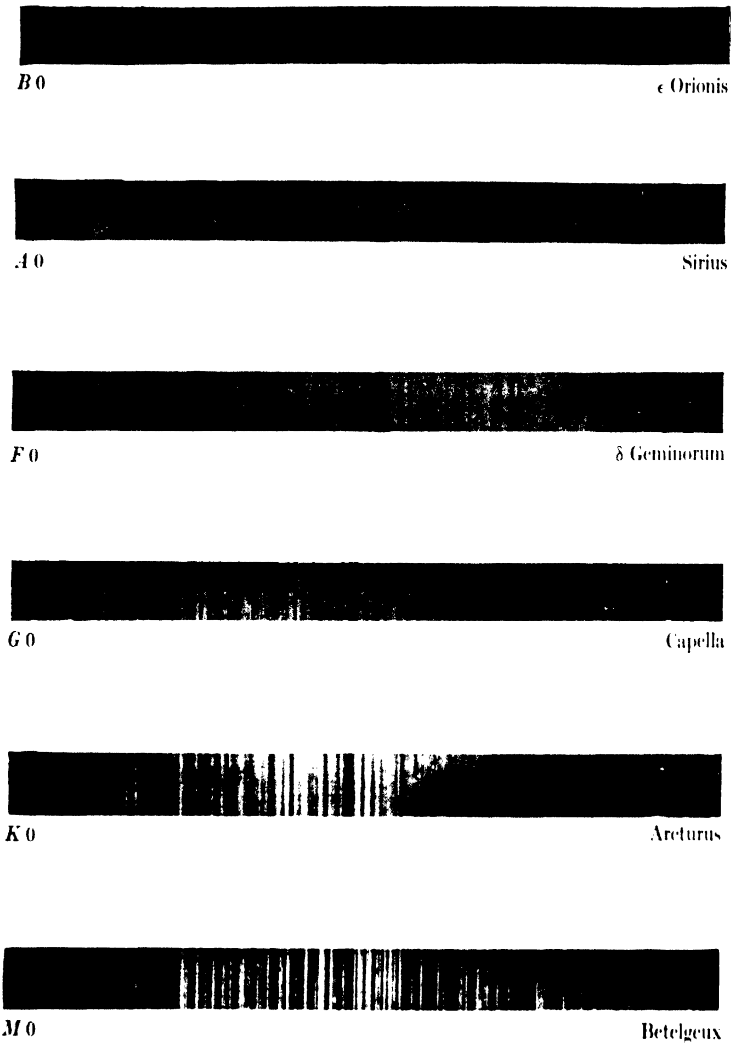
Although the non-metals are even more abundant, it is less easy to determine their amounts with accuracy. Hydrogen alone is many hundreds of times more abundant than all the metals added together—various estimates give factors ranging from 600 to 2500. Oxygen appears to come next in order of abundance, but is a very poor second, being perhaps only a twentieth as abundant as hydrogen. Then come nitrogen and carbon with only about the abundance of silicon and sodium.

Generally speaking, the heavier elements are far less plentiful than the lighter in the sun's atmosphere. This can be readily explained by their natural tendency to sink to layers in which they are inaccessible to observation, but it is becoming increasingly clear that this is not the whole of the explanation, and it may not even be the explanation at all. It is remarkable, for instance, that elements of even atomic number (see p. 124 below) are more abundant than considerably lighter elements whose atomic numbers are odd. For instance, the table on p. 53 shews that magnesium is more abundant than the lighter sodium, and silicon is more abundant than the lighter aluminium. A similar phenomenon is observable in the composition of the earth's crust. The heaviest elements do not appear to have sunk entirely to the earth's interior, and again there is a general tendency for elements of even atomic number to occur more plentifully than those whose atomic numbers are odd.

It is significant that practically all the chemical substances which are at all common on earth have been identified in the atmosphere of the sun. Of the 90 elements known on earth, 58 have been detected in the sun definitely and certainly, four more have been detected but not with absolute certainty, eighteen appear to be missing and the spectra of the remaining ten are so little known that detection would hardly be possible even if these elements were present.

The researches of Miss Payne at Harvard and of Adams and Russell at Mount Wilson suggest that the chemical composition of all stars is much the same. Although the stars shew very varied spectra, these variations are found to indicate differences of temperature (and to a lesser degree of pressure) rather than of chemical constitution. For instance, when stellar atmospheres are at one special temperature, the

PLATE IX



Stellar Spectra

(The spectral types are indicated on the left)

spectrum of hydrogen is very strong; at a lower temperature it becomes far weaker, while that of iron becomes stronger. The older spectroscopists were in error in supposing that the former star contained more hydrogen and less iron than the latter; the explanation is merely that the atmosphere of the former star is hot enough to give the hydrogen the needed chance to proclaim its presence, while that of the latter is not.

SPECTRAL TYPES. Knowing that a star's spectrum depends primarily upon the temperature of its surface, it follows that stellar spectra can, in the main, be arranged in a single continuous sequence. Their usual classification is by a sequence of letters, *O*, *B*, *A*, *F*, *G*, *K*, *M* with decimal subdivisions, the temperature falling as we pass along the sequence, so that *O*-type stars have the highest surface temperatures and *M*-type stars the lowest. Examples of stellar spectra are shewn in Plate IX, their spectral types being indicated on the left.

SPECTROSCOPIC VELOCITIES. When a star's distance is known, its motion across the sky tells us its speed in a direction at right angles to the line along which we look at it—i.e. across the line of sight—but provides no means of discovering its speed along this line. We cannot see the motion of a body which is coming straight towards us, and a star moving at a million miles a second in a direction exactly along the line of sight would yet appear to be standing still in the sky. To evaluate velocities along the line of sight, the astronomer calls in the aid of the spectroscope.

When the light received from a star is analysed in a spectroscope, the pattern of lines or bands may be found to be shifted bodily in one direction or the other. If the shift is towards the red end of the spectrum, the light emitted by the star is reaching us in a redder state than that in which it ought normally to be, and

as red light has the longest wave-length, this means that every wave of light is longer—more drawn out—than normal.

As all light travels through space with the same speed, this means that fewer waves reach us than would normally be the case. This may be because we are receding from the star, or it from us, or a mixture of both reasons. In any case when the spectral pattern is displaced towards the red end of the spectrum we know that the distance between ourselves and the star is increasing. In the same way, a displacement towards the violet end shews that the distance between our selves and the star is decreasing, or in brief, the star is approaching. The shift of a spectrum resulting from the motion of the body which emits it is generally described as the "Doppler Effect."

Examples of this are shewn in Plate X (p. 58). The topmost line on the plate shews a small portion of the violet-blue region of three spectra, the middle one being that of the star μ Orionis while the other two above and below (which are identical) are "comparison" spectra shewing the normal positions of certain spectral lines of a star of this type—i.e. the position when the star is neither advancing towards us nor receding from us. Careful inspection shews that the stellar spectrum is displaced slightly to the right—i.e. towards the red end of the spectrum—shewing that the star must be receding from us.

The line below this shews the spectrum of the same star taken at a different date. Again we notice the displacement towards the red end, but we see that it is greater than before. When this second spectrogram was taken the star must have been receding more rapidly than when the first was taken.

When the amount of displacement of the lines of the spectrum of any object can be measured with accuracy,

a surprisingly simple calculation will tell us the speed with which the object is moving towards or away from us. For instance, if each line or band in a stellar spectrum is found to represent a wave-length a hundredth of one per cent. longer than that usually associated with it, then the star is receding from us with a speed of a hundredth of one per cent. of the velocity of light, or 186 miles a second—and similarly for all other displacements.

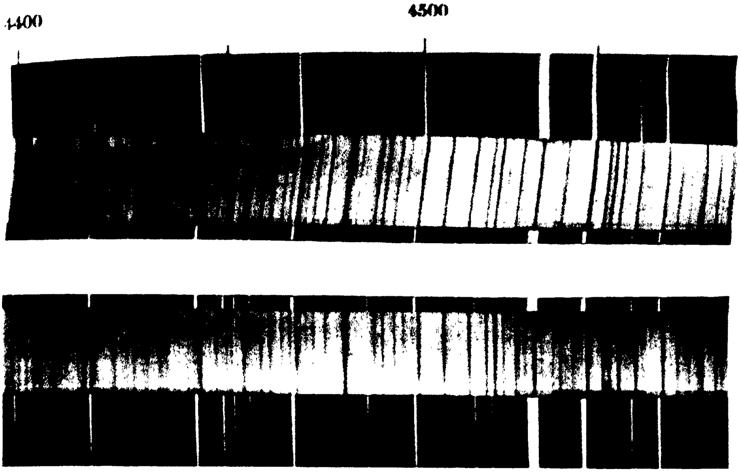
SPECTROSCOPIC ROTATION. By watching the motions of sun-spots across the surface of the sun, we find that the sun's atmosphere, in the proximity of its equator, rotates approximately once every 24¾ days. It follows that every point on the sun's equator is moving round the sun's centre with a speed of, roughly, 6000 feet a second. This means that points at the western end of the sun's equator are receding from us at 6000 feet a second while points at the eastern edge are advancing towards us at the same speed. If the sun stood still, its light would shew the normal spectrum for a star of its type, but as the result of its rotation, half of its surface emits light in which the spectral pattern is shifted to the red end, while the other half emits light in which the pattern is shifted in the other direction. The consequence is that every line of the normal spectrum is broadened out into a band of appreciable width. Moreover, by studying the observed widths of these lines, it is possible to calculate the speed of motion of points on the sun's equator, and hence the sun's rate of rotation.

Quite recently this method has been applied to the rotations of stars other than the sun, and it is now possible to state the speeds of equatorial motion of a great number of stars. When the sizes of the stars are known (p. 280) it is an easy matter to deduce their periods of rotation.

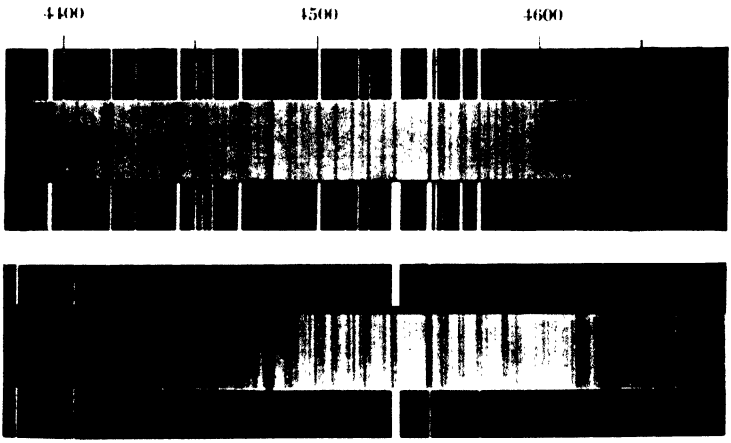
An example is provided by the lower half of Plate X, which exhibits the spectrum of the binary star ζ Ursae Majoris on two separate occasions. It is well to look at the lower line first. In this we see each line of the "comparison" spectrum replaced by two lines in the spectrum of the star—one from each constituent of the binary system; their displacements of course tell us the speeds of motion of the constituents. In the upper line, the lines are no longer distinct, shewing that the two constituents are now advancing or receding at equal speeds.

If an astronomer were acquainted with the orbital motions of the two components of a binary system, he might proceed to calculate with what speeds these components would move in the direction of the line of sight, and could then predict to what extent the two spectra ought to be displaced if the light from the system were analysed in a spectroscope; the spectroscope would of course confirm his prediction.

It is more instructive to imagine the reverse process. Suppose that on analysing the light from a star, the astronomer obtains a composite spectrum in which the lines are doubled—as in the lower line on Plate X—and are found to shift rhythmically backwards and forwards about their normal positions. The fact that there are two spectra tells him that he is dealing with a binary system; if the rhythmic shift repeats itself every two years, he knows that its orbit takes two years to complete. He studies the star by direct vision and finds



Spectrum of μ Orionis shewing variable velocity



Yerkes Observatory

Spectrum of ζ Ursae Majoris shewing lines doubled

The Doppler Effect in Stellar Spectra

it is a binary system in which the constituents revolve about one another every two years.

He examines another spectrum, and finds that it shifts rhythmically every two days. On looking directly at this star he can only see a single point of light. In spite of this he knows that there must be two stars, but the mere fact that they get around one another in so short a time as two days proves that they must be very close to one another, and he need feel no surprise that his telescope has failed to separate the image into two distinct points of light. Systems of this kind, which the spectroscope shews to be binary, but which the telescope usually shews as a single point of light, are called "spectroscopic binaries." Over a thousand such systems are known.

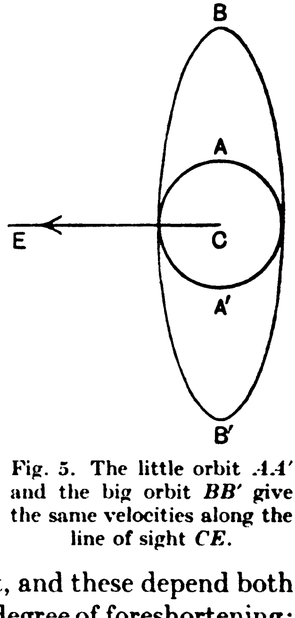


Fig. 5. The little orbit AA' and the big orbit BB' give the same velocities along the line of sight CE.

If the astronomer tries to construct the orbit of such a system from the spectroscopic observations alone, he finds himself in difficulties. His observations only tell him the velocities along the line of sight, and these depend both on the actual speed and on the degree of foreshortening; the same velocity may arise either from a big orbit in a plane nearly at right angles to the line of sight, or from a much foreshortened little orbit. For this reason, it is impossible to calculate the actual orbit or the weights of the stars from spectroscopic observation alone.

ECLIPSING BINARIES. There is one exception. Suppose that a star's light is seen to diminish in amount

at regular intervals and subsequently to return to its original strength. The obvious interpretation of the diminution of light is that one component of the system is eclipsing the other, and this can only happen if the orbit is so completely foreshortened that its plane passes through, or at least very close to, the earth. In such a case it is possible to reconstruct the whole orbit, and thence to calculate the weights of the two components. Not only so, but the length of time during which the eclipses last tells us the actual sizes of the

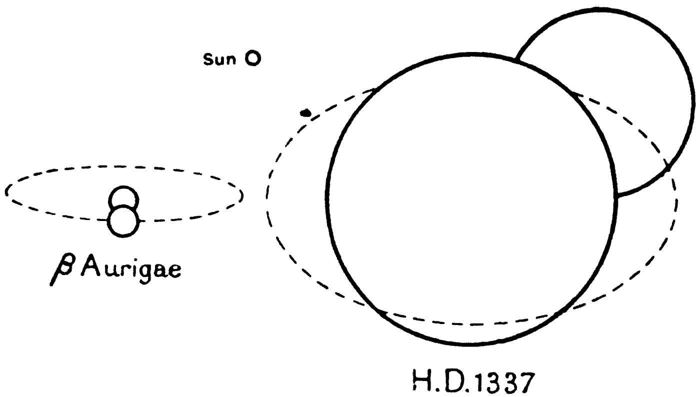


Fig. 6. Components and orbits of Eclipsing Binaries. (The broken lines represent the orbits of the smaller component round the larger.)

two components, so that it is possible to draw a complete picture of the system. Diagrams of the dimensions and orbits of two typical eclipsing binaries are shewn in fig. 6; these are drawn to the same scale, this being indicated by the small circle representing the sun.

When no eclipse occurs in a spectroscopic binary, there is no means of knowing how much foreshortening to allow for, but we can obtain a general idea of the weights of the components by assuming an average degree of foreshortening. If we assume different degrees of foreshortening in turn, we shall find that the

computed weights come out least when the plane of the orbit is assumed to pass through the earth—i.e. when the orbits are computed as though the system were an eclipsing one. Thus, although we cannot discover the actual weights of the components of a non-eclipsing binary, we can always state limits above which they must lie, namely the weights computed as though the system were an eclipsing one. It is in this way that we know that the two components of Plaskett's star (p. 51) must have more than 75 and 63 times the weight of the sun.

VARIABLE STARS

The majority of stars shine with a perfectly steady light, so that we can say that a star is of so many candle-power. The sun, for instance, emits a light of $3{\cdot}23 \times 10^{27}$ candle-power.

Yet there are classes of exceptional stars in which the light flickers up and down. In some, as in the eclipsing binaries just described, the light-fluctuations are quite regular, repeating themselves with such precision that the stars might well be used as time-keepers. In others the fluctuations, though not perfectly regular, are nearly so, while still others exist in which the fluctuations appear at present to be completely irregular, although no doubt the changes in these will be reduced to law and order in due course. For our present discussion, the various types of irregular variables are not of great importance.

CEPHEID VARIABLES. The really interesting stars are those of a certain class of regular variable, generally called "Cepheid variables," after their prototype, the star δ Cephei. The physical nature of these stars and the mechanism of their light-fluctuation is still far from being understood; competing theories are in the field,

the discussion of which lies beyond the range of the present book.

Whatever their mechanism may be, observation shews that these stars possess a certain definite property, which proves to be of the utmost value. This being so, we may accept it gratefully without troubling as to its why and wherefore. The perfectly regular light fluctuations of the eclipsing binaries would make them suitable for measuring time even though we did not understand the mechanism behind these fluctuations. In the same way the fluctuations of Cepheid variables have a quality which makes them valuable for measuring space—we can use them as measuring-rods with which to survey the distant parts of the universe. In brief, this property is that we can deduce the intrinsic brightness of these stars, and so their distances, from their observed light-fluctuations.

The light-fluctuations are so distinctive as to make the stars easy of detection and recognition. There is a rapid increase of light, followed by a slow gradual decline; then again the same rapid increase and slow decline as before. It is as though someone were throwing armfuls of fuel on to a bonfire at perfectly regular intervals.

One other class of variable stars, generally known as "long-period variables," shews somewhat similar light-fluctuations, but the two classes are easily distinguished by their very different periods of light-fluctuation. The light-fluctuations of the Cepheid variable are by far the more rapid, the complete cycle seldom occupying more than about a month, and more generally being a matter only of a few days or hours. Cepheid variables in Globular Clusters (p. 69), often described as "Cluster variables," frequently complete their cycles in periods of six to ten hours; one has just been discovered in the cluster ω Centauri with a period which appears to be

less than an hour and a half. On the other hand, the full cycle of the long-period variable generally occupies about a year.

Fig. 7 (p. 64) shews the light-curves of typical variable stars of the different classes. In each diagram the progress of time is represented by motion across the page from left to right; the higher the fluctuating curve is above the horizontal line at any instant, the brighter the star at that instant.

Out near the boundary of the galactic system is a cluster of stars known as the Lesser Magellanic Cloud (Plate XXVI, p. 235), in which Cepheid variables occur in great profusion. In 1912 Miss Leavitt of Harvard found that the light of the brighter Cepheid variables in this cloud fluctuated more slowly than the light of the fainter ones. Whatever was responsible for turning the stellar lights up and down, it acted more rapidly for feeble than for brilliant lights. If a number of Cepheid variables were at different distances from the earth, their apparent brightnesses would of course depend only in part on their intrinsic brightness or candle-power, but the stars in the Magellanic Cloud are all, nearly enough, at the same distance from the earth. Thus, differences in the apparent brightnesses of stars in this cloud could only represent real differences of intrinsic brightness, and Miss Leavitt's discovery could be stated in the form that the period of light-fluctuation of a Cepheid depended on its candle-power. Although this was only proved to be true for the Cepheids in the Magellanic Cloud, it must be true for all Cepheids wherever they are, for it is inconceivable that we could make a star's light fluctuate more slowly or more rapidly merely by altering its distance from us—by ourselves receding from it, in fact.

Professor Hertzsprung of Leiden and Dr Shapley, then of Mount Wilson Observatory, were quick to

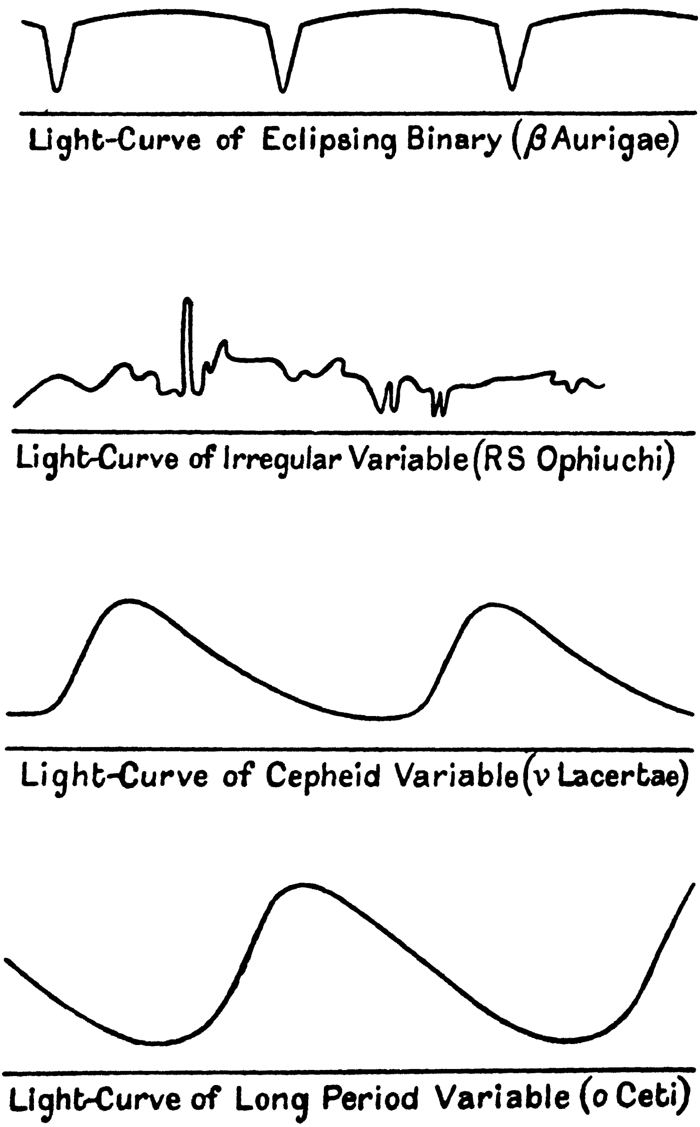


Fig. 7. Light-curves of typical Variable Stars of different classes.

seize upon the implications of this discovery. They saw that if two Cepheids *A*, *B* in different parts of the sky are found to fluctuate with equal rapidities, then their intrinsic candle-powers must be equal. Thus, any difference in their apparent brightness must be traceable to a difference in their distances from us. If *A* looks a hundred times as bright as *B*, then *B* must be at ten times the distance of *A*. In the same way, a third Cepheid *C* may prove to be at ten times the distance of *B*. We now know that *C* is a hundred times as remote as *A*. And if *D* can be found ten times as distant as *C*, we know that *D* is a thousand times as remote as *A*. So we can go on constructing and ever extending our measuring-rod; there is no limit until we reach distances so great that even Cepheid variables, which are exceptionally bright stars, fade into invisibility.

So far we have only considered the comparative distances of Cepheids. The absolute distances of many of the nearer Cepheids have, however, been determined by the parallactic method already explained—i.e. by measuring their apparent motion in the sky, resulting from the earth's motion round the sun. Taking any one of these stars as our original Cepheid *A*, we can step continually from one Cepheid to another, and so calculate the absolute distances of all the Cepheid variables in the sky.

In this way the observed relation between the period of fluctuation and the brightness of Cepheid variables—commonly known as the "period-luminosity law"—can be made to provide a scale on which the absolute luminosity, or candle-power, of a Cepheid can be read off directly from the observed period of its light-fluctuations. The Cepheid variables may be regarded as lighthouses set up in distant parts of the universe. We can recognise them, just as a sailor recognises lighthouses, by the quality and regular

fluctuations of their light. We can read off their candle-power from the period of these fluctuations as easily as the sailor could read off the candle-power of a lighthouse from an Admiralty chart. The apparent brightness of the Cepheid informs us as to its distance from us. For instance, Cepheids whose light fluctuates in a period of 40 hours are approximately 200 times as luminous as the sun, and so are of $6{\cdot}46 \times 10^{29}$ candle-power; a period of ten days indicates a luminosity 1600 times that of the sun, or a candle-power of $5{\cdot}17 \times 10^{30}$, and so on. If a star in a distant astronomical object is observed to fluctuate with a period of ten days, and the quality of its fluctuations shew it to be a Cepheid variable, we know that its actual candle-power must be $5{\cdot}17 \times 10^{30}$. Its apparent brightness is observed to be that of a star of, say, magnitude 16, which, stripped of technicalities, means that we receive as much light from it as from a single candle at a distance of 570 miles. The difference between one candle and $5{\cdot}17 \times 10^{30}$ candles accordingly results from the difference between 570 miles and the distance of the object in question, whence, since light falls off as the inverse square of the distance, we calculate that the distance of the object must be about 220,000 light-years.

It would be difficult to over-estimate the importance of all this to modern astronomical science. It provides us with a means for surveying, if not the whole of the universe, at least those parts of it in which Cepheid variables are visible. Actually this last reservation is unimportant, for Cepheid variables are very freely scattered in space. Naturally the method is of most value for the exploration of the most distant parts of the universe; here it achieves triumphant success where other methods fail completely. The parallactic method begins to fail when we try to sound distances of more than about a hundred light-years. The ap-

parent path in the sky, which a star at this distance describes in consequence of the earth's motion round the sun, is of the size of a pin-head two miles away. With all their refinements, modern instruments find it difficult enough to detect so small a motion as this, and it is practically impossible to measure it with accuracy.

The difficulties of measurements based on the "period-luminosity" law are of a different kind. Even the nearest Cepheids are so remote that it is difficult to determine their absolute distances with any great accuracy, either by the parallactic or by any other method. Thus the "period-luminosity" law provides us with a measuring-rod which can be used with equal confidence throughout almost any distance, but we do not know the absolute length of the rod with great accuracy. The question is still under discussion. A recent careful study of Gerasimovic (1931) suggests that the measuring-rod may have only about 63 per cent. of its previously assumed length. It is clear at least that some reduction of earlier estimates of distance is called for; in the present book many have been reduced to about 63 per cent. of their original values and are stated in round numbers only. It should be borne in mind that they may still be in error by perhaps 10, and possible even 20 per cent. Even so, it is still true that the "period-luminosity" law measures the distances of objects up to a million light-years away, with a smaller percentage of error than is to be expected in the parallactic measures of stars only a hundred light-years away.

SOUNDING SPACE

This by no means exhausts the list of modern methods of surveying space. Any standard type of astronomical object, which is easily recognisable and emits the same

amount of light no matter where it occurs, provides an obvious means of measuring astronomical distances, for when once the intrinsic luminosity of such an object has been determined, the distance of every example of it can be estimated from its apparent brightness.

Cepheid variables of assigned periods provide the most striking instance of such standard objects, but three others are available, although they are not so generally useful as Cepheids. First comes another type of variable star, the "long-period variables" already mentioned, which are generally similar to Cepheids except that their light fluctuates much more slowly. These stars are intrinsically far more luminous even than Cepheids, many of them being 10,000 times as luminous as the sun. They are accordingly visible at enormous distances, and may ultimately be found to provide a means of sounding depths of space so remote that even Cepheids are lost to sight.

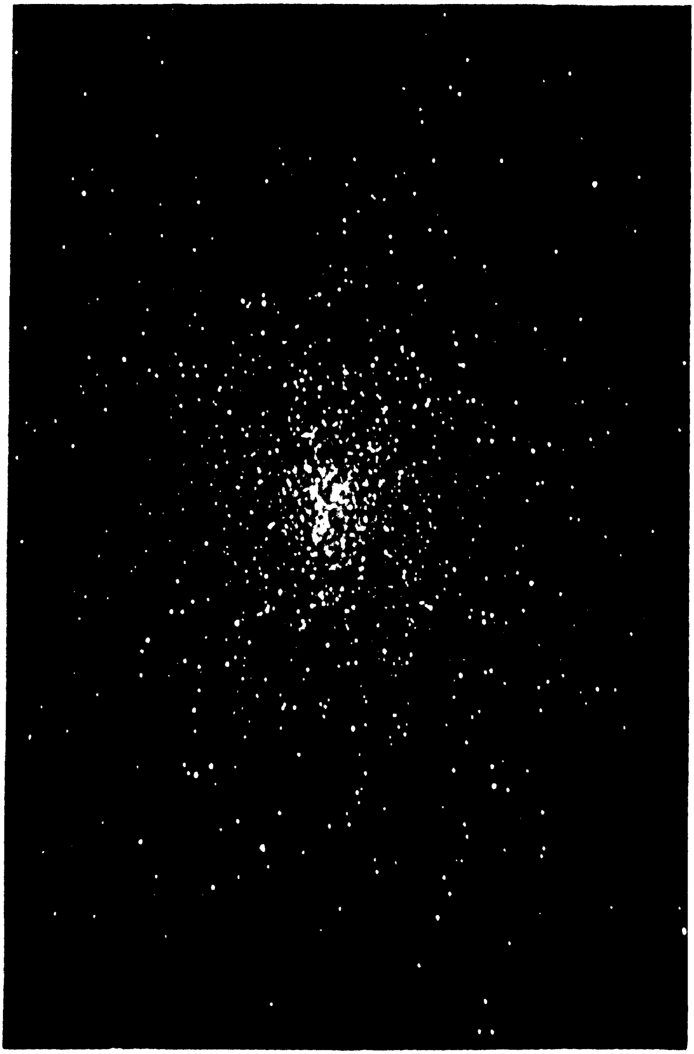
Next come "novae" or new stars. Every now and then an ordinary star in the sky suddenly bursts out in a phenomenal blaze of light, shining with perhaps a thousand times its original brilliance. The cause of these violent outbursts is still a matter for debate, and no thoroughly convincing explanation has as yet been given. A study of comparatively near novae has, however, disclosed the surprising fact, for which no explanation has yet been found, that all novae attain to approximately the same maximum luminosity—about 25,000 times that of the sun. Thus novae, when at their brightest, provide standard objects of the kind in question, and as novae appear in various parts of the sky, and particularly in the extra-galactic nebulae, they provide a rough means of measuring stellar and nebular distances.

Blue stars provide yet another method. These are exceedingly luminous, and it is found that blue stars

E. E. Barnard

The Star-cloud in Sagittarius

PLATE XII



Dominion Astrophysical Observatory, B.C.

The Globular Cluster *M* 13 in Hercules

of the same spectral type shew only a small range of luminosity *inter se*. Thus, blue stars are further objects of standard luminosity, and this makes it possible to determine the distances of blue stars, and so of course of the astronomical objects in which they occur.

Even this does not exhaust the possible ways of determining stellar distances. Two other methods of a quite distinct kind remain. Dr W. S. Adams, Director of Mount Wilson Observatory, and others have found that certain definite peculiarities in the spectra of certain classes of stars convey information as to the density of the atmosphere of the star emitting them. This density is related to the star's physical structure and this in turn to its absolute luminosity; knowing this, it is easy to estimate the star's distance from its apparent brightness. This is sometimes described as the method of "Spectroscopic Parallaxes"—an unhappy and misleading bit of jargon, since a parallax is an angle, and the method has nothing to do with angles.

Finally the diffuse cloud of nebular matter which is spread through interstellar space (p. 31) is found to affect the quality of light travelling through it in such a way that a star's spectrum gives some slight indication of the amount of cloud through which the light of the star has travelled, and this again provides a rough means of estimating distances inside the galactic system.

GLOBULAR CLUSTERS. The law of Cepheid luminosity was first used by Hertzsprung to estimate the distance of the Lesser Magellanic Cloud, the study of which had been responsible for the original discovery of the law. Shapley subsequently used it to determine the distances of the rather mysterious groups of stars known as "Globular Clusters." A typical example of these is shewn in Plate XII. About 100 of these clusters are known and they all look pretty much alike, except

for differences in apparent size. Even these latter can be traced mainly to differences of distance, so that the globular clusters are probably almost identical objects, and Plate XII might almost be regarded as a picture of any one of them. Cepheid variables abound in them all.

Shapley originally estimated that the nearest globular cluster, ω Centauri, was at a distance of about 22,000 light-years, the farthest, N.G.C. 7006, being about ten times as remote, at a distance of 220,000 light-years. If we reduce these in the way suggested on p. 67, they become 14,000 and 140,000 light-years respectively. At such distances the parallactic method of measuring distances would of course fail hopelessly. The parallactic orbit of a star at 140,000 light-years' distance is about the size of a pin-head held at a distance of 3000 miles; no telescope on earth could detect, still less measure, such an orbit.

Such figures as 140,000 light-years can convey but little conception of the distance of this remotest of star-clusters from us. We may apprehend it better if we reflect that the light by which we see the cluster started on its long journey from it to us at a time when primaeval man still roamed over the earth. Through the childhood, youth and age of thousands of generations of men, through the long prehistoric ages, through the slow dawn of civilisation and through the whole span of time which history records, through the rise and fall of dynasties and empires, this light has travelled steadily on its course, covering 186,000 miles every second, and is only just reaching us now. And yet this enormous stretch of space does not carry us to the confines of the universe; we shall now see that in all probability it has barely carried us to the confines of the galactic system.

Shapley has mapped out the complete system of the globular clusters, and finds that they occupy an oblong

region, lying on both sides of the plane of the Milky Way, its greatest diameter lying in this plane, and its two transverse diameters being considerably shorter. The sun is nearer to the edge of this oblong region than to its centre, which explains why all the globular clusters appear in one half of the sky, as Hinks first noted in 1911. The general arrangement is shewn in fig. 8. The page of the book represents the plane of the

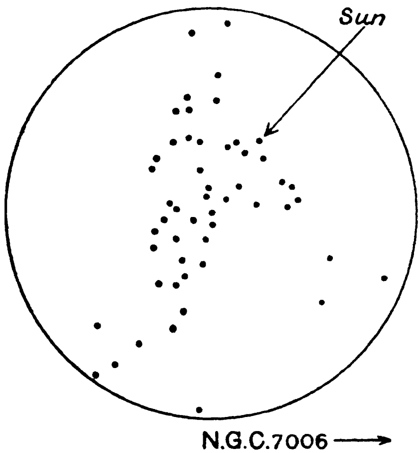


Fig. 8. The arrangement of the Globular Clusters.

Milky Way, the various dots representing the points in this plane which are nearest to the different clusters, so that the diagram exhibits the system of globular clusters as they would appear to an observer out in space who viewed the galactic plane "full-on." According to Shapley's original estimates, all the globular clusters except N.G.C. 7006 lie within a circle of about 125,000 light-years' radius, having its centre at about 50,000 light-years from the sun. These distances must probably be reduced by something like the 37 per cent. mentioned on p. 67.

THE ARRANGEMENT OF THE GALACTIC SYSTEM. Although the matter was for long one of vigorous controversy, it is now becoming clear that the region of space mapped out by these globular clusters approximately coincides with that occupied by the galactic system itself. Herschel and Kapteyn appear to have been in error in supposing the centre of the galactic system to be in the neighbourhood of the sun; a considerable accumulation of evidence indicates that it lies in a massive star-cloud in the constellation of Sagittarius (see Plate XI, p. 68)—the richest part of the Milky Way, as might be expected. Dr Shapley and Miss Swope, at Harvard Observatory, determined the distance of this star-cloud from the sun as 47,000 light-years, which places it almost exactly at the centre of the system of globular clusters, as shewn in fig. 8.

If we reduce this by 37 per cent., for the reasons explained on p. 67, we are left with a distance of 30,000 light-years. There is, however, great uncertainty about the exact distance, other and more recent estimates making it even smaller than 30,000 light-years.

Even so, it is clear that the sun is very far from the centre of the galactic system. Investigations by Shapley, Seares of Mount Wilson, and others have shewn that there is a local concentration of stars—millions in number, and many of them of well above average brightness—surrounding the sun. This is commonly described as the "local system" or "local cluster," and the error of identifying this with the main galactic system has apparently been responsible for a large part of the confusion which has hitherto beset the problem of the architecture of the galaxy. This local system has the same flattened shape as the main system, but it does not lie exactly in the plane of the Milky Way, being inclined at an angle of about 12 degrees to it. The sun appears to lie very near to the

central plane of the galactic system—so near indeed that it is impossible to say whether it lies to the north or south of this plane; in any event Seares finds that it probably does not lie more than 25 light-years away from this plane. On the other hand, the sun lies distinctly to the north of the central plane of the local system, according to Seares perhaps about 150 light-years to the north. Fig. 9 shews a cross-section of the system, as it is now imagined to lie.

We have already compared the shape of the galactic system to that of a wheel. It obviously could not retain this shape if the stars which formed it were standing still in space. For the gravitational pull of the inner stars would cause the outermost stars—the rim of the

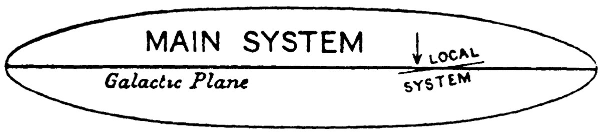


Fig. 9. Diagrammatic scheme of cross-section of the Galactic System. The sun is at the head of the arrow.

wheel—to fall inwards, and the system would end as a confused jumble of stars somewhere in the vicinity of the hub of the wheel. In 1913 Henri Poincaré, Professor of Mathematics at the Sorbonne, suggested that the galactic "wheel" might escape this fate if it were in a state of rotation. Just as the earth's motion saves it from falling into the sun—or, to take a rather closer analogy, just as the rotation of Saturn's rings saves the particles which form the rings from falling on to Saturn—so Poincaré suggested, the stars which form the rim of the wheel might be saved from falling into the hub, by a motion of rotation of the whole wheel. A rough calculation suggested that it would be necessary for the wheel to rotate at the rate of a complete revolution about every 500 million years.

Naturally it is no simple matter to detect so slow a rotation. It was first suspected to occur in the following way. We know that when a spinning-top or gyroscope is set in rapid rotation, a considerable force is needed to twist the top or gyroscope about in space. This is the principle of the gyroscopic compass such as is used to steer ships. A gyroscope, a sort of big steel spinning-top, is started spinning with its two ends pivoted in a swinging frame. No matter how the ship turns, the motion of the gyroscope keeps the frame pointing always in the same direction, and by the help of this fixed direction the ship is kept on its course. Now the solar system has many of the properties of a huge spinning-top, the revolutions of the planets corresponding to the spin of the top. As there is no twist impressed on this "spinning-top" from outside, its axis of rotation must always point in the same direction, thus providing a sort of "gyroscopic compass" to give us our bearings in space.

In 1913 Charlier believed he had found that this "gyroscopic compass" was turning round against the distant background of the Milky Way, at the rate of a complete rotation every 370 million years, a period which subsequent measurements increased to 530 million years. Eddington then suggested that it might be the background rather than the gyroscopic compass that was turning, the Milky Way actually rotating in the way imagined by Poincaré, and at just about the rate which Poincaré had calculated.

Recent investigations by Oort, Plaskett, Lindblad and others prove beyond doubt that such a rotation really occurs, although it is of a more complicated type than the simple "cart-wheel" rotation we have so far discussed. In the solar system the innermost planets move more rapidly than the outermost: they must necessarily do so if the motion of each planet is to

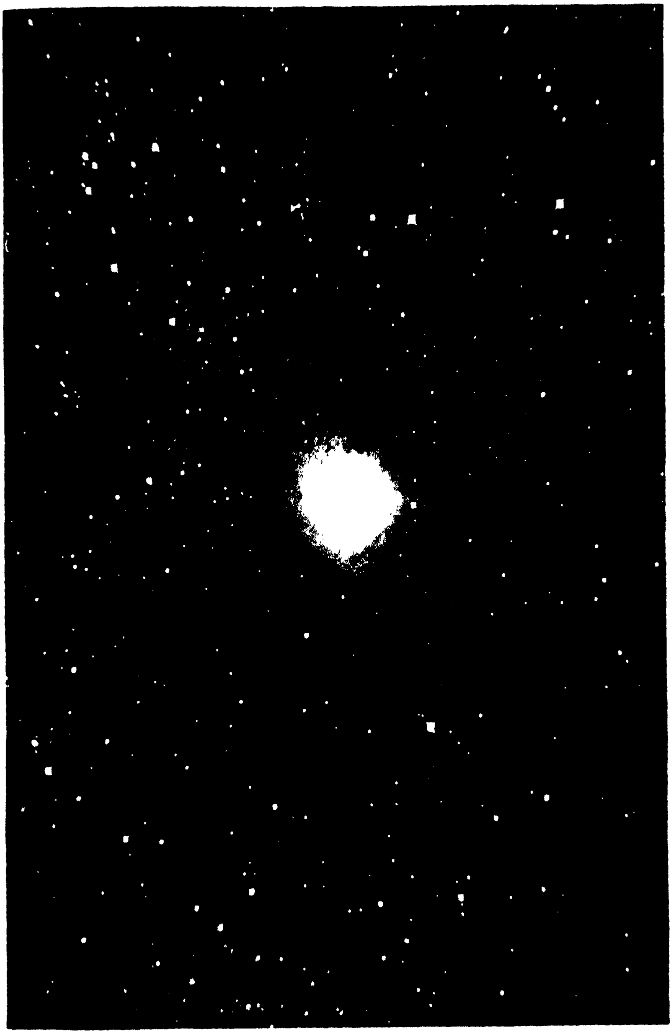
counteract the sun's attraction. In the same way, if the rotational motion of the galaxy is to counteract the gravitational attraction of its innermost stars, its inner parts must rotate more rapidly than its outermost. Thus the sun ought to be overtaking those stars which lie outside it on the galactic wheel, while being itself overtaken by those which lie inside it. Such an overtaking motion is fairly easy to detect. A careful analysis of observed stellar motions has disclosed such a motion, shewing that the galaxy as a whole is in rotation in precisely the way just described, the inner parts rotating most rapidly.

The hub of this gigantic wheel lies almost exactly in the direction which Shapley assigned to the centre of the galaxy from his study of the globular clusters. Its distance from the sun, which cannot yet be determined with any great accuracy, is probably somewhere about the 30,000 light-years already mentioned. To within the limits of accuracy which are at present attainable, this places the centre of the galactic wheel at the centre of the system of globular clusters (see fig. 8, p. 71). In the vicinity of the sun the galactic wheel performs a complete revolution in a period of about 250 million years, a time which can be estimated far more closely than the distances with which we have been concerned. This endows the stars near the sun with a motion through space at a speed of about 140 miles a second, arising from the rotation of the galaxy alone.

These data make it possible to weigh the stars of the galactic system *en masse*, using precisely the same method as we use to determine the weights of the sun or of Jupiter. Individual stars far away from the centre of the galactic system must be describing orbits under the gravitational pull of the system as a whole—the pull which prevents the stars from scattering away into space, and so keeps the galactic system in being. The

aggregate of these orbital motions produces the general rotation of the galaxy which we have just discussed. And from the figures just mentioned, it can be calculated that the total weight of matter inside the sun's orbit must be about that of 110,000 million suns. Other estimates of the weight of the galaxy have been made, generally lower than the foregoing. Two estimates by Lindblad, for instance, give the total weight of the galaxy as 110,000 and 180,000 million suns respectively. Part of this may of course arise from interstellar dust or gas. Nevertheless, as the average star weighs considerably less than the sun, the total number of stars in the galactic system may well be of the order of 200,000 million. This estimate of course includes all stars, dark as well as luminous.

Again we are confronted with the difficulty of visualising such large numbers. With perfect eyesight on a clear moonless night we can see about 3000 stars. Imagine each of these 3000 stars to spread out into a complete sky-full of 3000 new stars, and we are contemplating 9 million stars, which is still only the number visible in a telescope of 5 inches aperture. We probably cannot ask our imagination to play the same trick for us a second time, but if it can be persuaded to do so, and if we can think of each of these 9 million stars as again generating a whole sky-full of stars, we still have only 27,000 million stars within our purview—a number which is still far below any permissible estimate of the total number of stars in the galactic system. Or again, let us notice that the number of stars photographically visible in the 100-inch telescope, namely 1500 million, is about equal to the number of men, women and children in the world. Each inhabitant of the earth—each man, woman and child living in the five continents or travelling on the seven seas—can be allowed to choose his own particular



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Magnification of the central region of the Great Nebula
M 31 in Andromeda

PLATE XIV

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Magnification of a part (left-hand top corner) of the Great Nebula *M* 31 in Andromeda, which is shewn complete in Plate VII (p. 32)

star, and can then repeat the process tens, and more probably hundreds, of times without going outside the galactic system.

After this we can still go exploring outside the galactic system and find more and ever more stars. The galactic system, with its hundreds of millions of stars, no more contains all the stars in space than one house contains all the inhabitants of Great Britain. There are millions of other houses and millions of other families of stars.

THE EXTRA-GALACTIC NEBULAE. We have already spoken of the faint nebulous objects which Herschel described, somewhat conjecturally, as "island universes." These are the other houses in which other families of stars are to be found. The most powerful of modern telescopes shew that they consist, in part at least, of huge clouds of stars. Just as a powerful microscope shews that a puff of cigarette smoke, in spite of its appearance of continuity, consists of a cloud of minute but quite distinct particles, so a powerful modern telescope breaks up the light from the outer regions of these nebulae into distinct spots of light; the nebula is resolved into a cloud of shining particles, just as the Milky Way was in Galileo's tiny telescope of three centuries ago. Plate XIV shews an example; it represents a magnification of a small area in the top left-hand corner of the Great Nebula *M* 31 in Andromeda already shewn in Plate VII (p. 32), and the resolution into distinct spots of light is unmistakable. We know that some at least of these spots of light are stars; Dr Hubble of Mount Wilson has found that many of them are Cepheid variables, their light shewing the unmistakable characteristic fluctuations of the familiar Cepheid variables nearer home. The other shining particles are of comparable brightness and shew about the range of brightness above and below

that of the Cepheids which is needed to justify us in supposing that they are ordinary stars. Not only so, but Dr Hubble has observed outbursts in no fewer than 85 stars in this nebula which exactly reproduce the familiar characteristics of the outbursts of novae in the galactic system. He has also found four stars which reproduce all the well-known features of long-period variables, and, even more recently, has discovered objects precisely similar to the globular clusters of the galactic system. Thus, there is little room for doubt that the nebula is essentially a cloud of stars, with many similarities to our own galactic system. Seares has suggested that the "local cluster" of stars surrounding our sun (p. 72) may be very similar to the knots or condensations observed in the arms of spirals; he considers that all the known peculiarities of stellar distribution are well explained, qualitatively at least, by this hypothesis.

From the observed periods of fluctuation of their Cepheid variables, Dr Hubble estimated the distance of the Andromeda nebula as about 855,000 light-years. The somewhat similar nebula *M* 33 shewn in Plate XXV (p. 234) proved to be at the slightly smaller distance of about 830,000 light-years. Other astronomers have made similar estimates, Dr Lundmark of Lund, for instance, has estimated the distances of the two nebulae just mentioned at 860,000 and 840,000 light-years respectively, and similar estimates have been made from observations on the maximum brightness of the novae in the nebula, by assuming that these attain to the same maximum brightness as the novae of the galactic system.

Possibly these estimates ought to be reduced to something like 68 per cent. of their values for the reasons explained on p. 67. This would leave the distance of the Andromeda nebula at about 540,000

light-years, and that of the nebula *M* 33 at about 520,000 light-years. Even with these reduced distances it is clear that these nebulae lie right outside the galactic system, justifying the term "extra-galactic" nebulae.

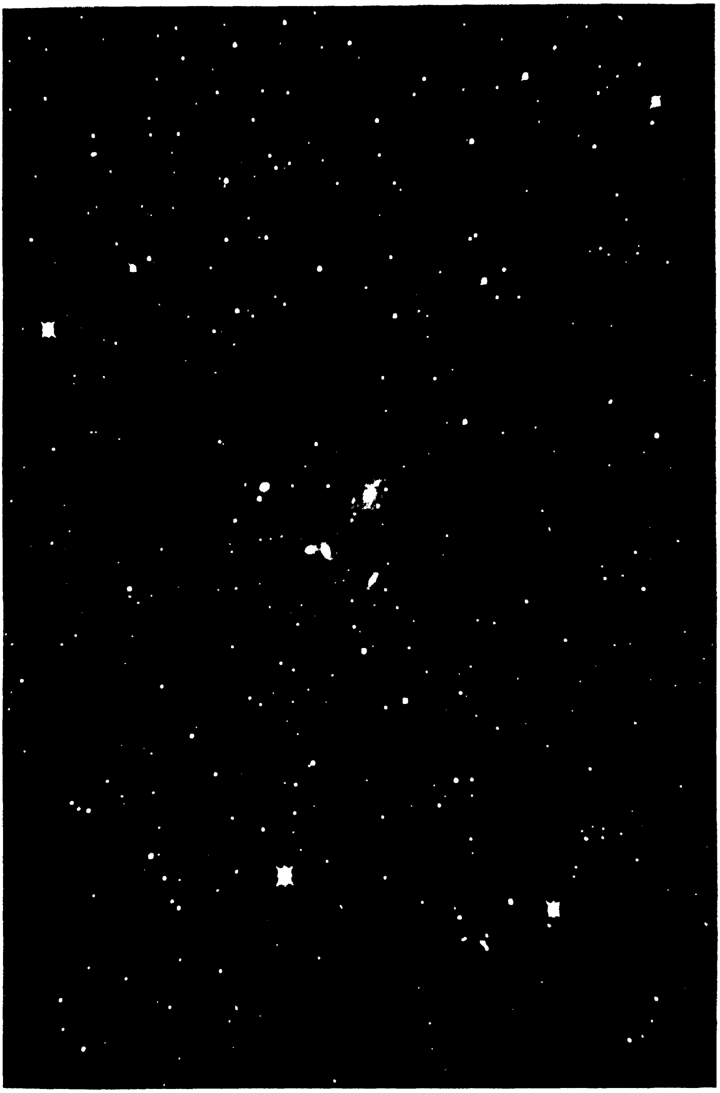
One might attempt to estimate the total number of stars in these nebulae by counting those visible in a selected average small area, but more precise methods are available. Just as we have supposed that the outermost stars in the galactic system are describing orbits under the gravitational attraction of the galaxy as a whole, so we must suppose that the outermost stars in a nebula are describing orbits under the gravitational attraction of the main mass of the nebula; the forces which keep them from running away from the nebula are similar to those which keep the earth moving in its orbit round the sun. If so, we can weigh the nebulae, precisely in the same way as we weigh the sun (p. 47) or the galactic system (p. 75). In this way Dr Hubble originally estimated that the weight of the Great Nebula *M* 31 in Andromeda, shewn in Plate VII, must be about 3500 million times that of the sun, while the nebula N.G.C. 4594 in Virgo, shewn in Plate XXI (p. 230), must have about 2000 million times the weight of the sun. If all nebular distances have to be reduced in the way just explained, this estimated weight must be reduced by the same factor. In a general way we may say that probably each of the extra-galactic nebulae contains about enough matter to make some 2000 million stars, each of the weight of the sun, or perhaps about 4000 million stars of average weight.

This is not the same thing as saying that each nebula already contains 4000 million stars. While many of these nebulae appear to consist largely of clouds of stars, yet most of them contain also a large central region which no telescopic power has so far succeeded

in resolving into distinct points. For instance, Plate XIII shews the central region of the Great Nebula in Andromeda magnified to the same degree as the left-hand top corner shewn in Plate XIV, and this is clearly not resolved into stars in the same way as the outer regions shewn in Plate XIV. We shall find reasons later (Chapter IV) for interpreting the central regions of such nebulae as masses of gas which are destined in time to form stars, but have not yet done so. We shall in fact find that the nebulae are the birthplaces of the stars, so that each nebula consists of stars born and stars not yet born. It is the total weight of stars already born and of matter which is destined to form stars that aggregates 2000 million suns.

THE FAINTER NEBULAE. We have seen how longer and ever longer measuring-rods have been needed to conduct the survey of space. A standard metre rod, a baseline on the earth's surface, the radius of the earth's orbit, the distances of the nearest stars, the distances of the Cepheid variables—each has been found adequate up to a certain distance and then has had to give place to its successor of yet greater length. Finally even the Cepheid variables fail; the faintest of observed nebulae are obviously far beyond the distance at which we may hope to detect these stars.

Hubble has devised a new measuring-rod which serves after the Cepheid measuring-rod fails. It is possible to measure the apparent brightness of even the faintest nebulae, and also to measure the area of the sky they occupy. As regards nebulae of any one shape, Hubble finds that the apparent brightness is very approximately proportional to the area occupied, so that nebulae of similar shape are equally bright per unit of surface. This suggests that nebulae of the same shape are similar structures, their differences of apparent brightness and size resulting merely from dif-



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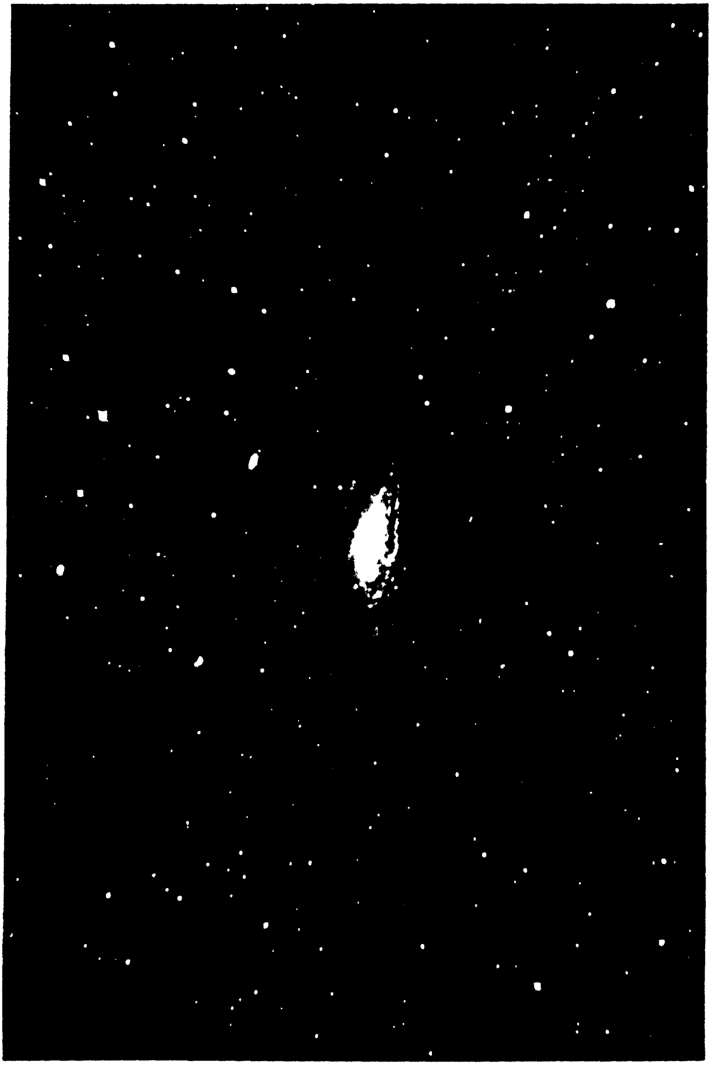
A compact Cluster of faint Nebulae in Pegasus

PLATE XVI



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The Nebula N.G.C. 7331 in Pegasus and a remote Cluster of faint Nebulae

ferences of distance. Here again then we come upon a series of standard objects, all of equal or approximately equal luminosity, and once again, as on p. 68, we can estimate the distance of any individual from its apparent brightness or faintness, or even more simply, from its apparent dimensions if these are large enough to measure. For instance, Plate XVI shews a cluster of nebulae in Pegasus, together with the single nebulae N.G.C. 7331 (in the centre of the Plate), which appears substantially larger. Actually we know it must be of approximately the same size as nebulae of the same shape in the cluster. As it appears about ten times larger, we know it must be ten times nearer.

Using this method, it is possible to calculate the distance of even the faintest of the nebulae, and to study the distribution of the nebulae in space.

About 2,000,000 of these faint extra-galactic nebulae can be seen in the great 100-inch telescope at Mount Wilson. They appear to be scattered through space with a tolerable approach to uniformity, their average distance apart being something of the order of 1,500,000 light-years although here and there this uniformity is broken by clouds and clusters of nebulae. For instance, a small and compact cluster, also in the constellation of Pegasus, is shewn in Plate XV. Again, the sky is remarkably rich in nebulae in the constellations of Virgo and Coma Berenices. Here, at a distance of some ten million light-years from the sun, Shapley finds that a cloud of about 300 nebulae is collected within a space having only from 5 to 10 times the dimensions of the galactic system. The same region of the sky appears also to contain three other and more remote clouds. Shapley has suggested that our galactic system, the Andromeda nebula and other near nebulae, may constitute a similar cloud.

THE REMOTEST DEPTHS OF SPACE. The most distant of all these 2,000,000 nebulae proves to be at a distance, in round numbers, of about 100 million light-years. This is the greatest distance which the human eye has so far seen into space. The 250,000 light-years which formed the diameter of the galactic system seemed staggeringly large at first, but we are now speaking of distances some 400 times greater. For more than 99 per cent. of its long journey, the light by which we see this remotest of visible nebulae travelled towards an earth uninhabited by man. Just as it was about to arrive, man came into being on earth, and built telescopes to receive it. So at least it appears when viewed on the astronomical scale. Yet even this last 1 per cent. or less of the journey covers the lives of tens of thousands of generations of men, through all of which, as well as through 100 times as great a span of time, the light has been travelling steadily onward at 186,000 miles a second.

There are so many faint nebulae at the very limit of vision of the 100-inch telescope, that it seems certain that a still larger telescope would reveal a great many more. The 200-inch telescope, which is shortly to be built, having twice the aperture of the present 100-inch, ought to probe twice as far into space, and so may perhaps be expected to shew about eight times as many, or 16 million, nebulae.

THE STRUCTURE OF THE UNIVERSE

So far every increase of telescopic power has carried us deeper and deeper into space, and space has seemed to expand at an ever-increasing rate. We may well ask whether this expansion is destined to go on for ever: are there any limits at all to the extent of space?

Even a generation ago, I think most scientists would

have answered this last question in the negative. They would have argued that space could be limited only by the presence of something which is not space. We, or rather our imaginations, could only be prevented from journeying for ever through space by running up against a wall of something different from space. And, hard though it may be to imagine space extending for ever, it is far harder to imagine a barrier of something different from space which could prevent our imaginations from passing into further space beyond.

The argument is not a sound one. For instance, the earth's surface is of limited extent, but there is no barrier which prevents us from travelling on and on as far as we please. A traveller who did not understand that the earth's surface is spherical, would naturally expect that longer and longer journeys from home would for ever open up new tracts of country awaiting exploration. Yet, as we know, he would necessarily be reduced in time to repeating his own tracks. As a result of its curvature, the earth's surface, although unlimited, is finite in extent.

THE THEORY OF RELATIVITY

Through his theory of relativity, Einstein claims to have established that space also, although unlimited, is finite in extent. The total volume of space in the universe is of finite amount just as the surface of the earth is of finite amount, and for the same reason—both bend back on themselves and close up. The analogy is valid and useful only so long as we are careful to compare the whole of space to the surface of the earth, and not to its volume. The volume of the earth is also finite in amount, but for quite different reasons. A mole which burrowed on and on through the earth in a straight line would come in time to

something which is not earth—it would emerge into the open air; but we can go on and on over the surface of the earth without ever coming to anything which is not the surface of the earth. The properties of space are those of the surface, not of the volume of the earth.

In the present book we can only glance very briefly at the steps by which the theory of relativity has led to this conclusion.

It is a matter of common observation that a moving body tends to persist in its motion unless something intervenes to check it: this describes the property of matter which we associate with the word "inertia." Newton enunciated this property of matter in his first law of motion:

> Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon,

and extended it in his second law to the case in which forces are in operation:

> The alteration of motion is ever proportional to the motive force impressed, and is made in the direction of the right line in which that force is impressed.

When objects such as cricket-balls or planets are seen to describe paths which are not straight, Newton concluded that there must be a force acting on them; in these two cases, it is the force of gravitation, which we have already discussed on p. 43. Newton's second law, just quoted, provided a means of measuring the amount of this force—it tells us that the force is proportional to the rate at which the moving body changes its speed. For more than two centuries this system of laws was believed to give a perfectly consistent and exact description of the processes of nature. Then, as the nineteenth century was approaching its close, certain experiments, commencing with the famous

Michelson-Morley experiment, shewed that the whole scheme was meaningless and self-contradictory.

Newton had measured force in terms of the change it produced in the speed of a moving body. Before we can measure a change of speed, we must be able to measure the speed itself, and to do this, we need some sort of background against which to measure it. Nineteenth century science had imagined such a background to be provided by an ether which filled all space. This all-pervading ether, in conjunction with the supposed steady onward roll of an ever-flowing river of time, provided all that was necessary for measuring speed, and so also changes of speed and force. The river of time rolled on for a second, as measured by a clock; at the end of this second the moving body was found to have advanced, let us say, ten feet through the ether, as measured by a measuring-rod, and we could then say its speed was ten feet a second.

The experiments in question shewed all these concepts to be illusory. No evidence could be found, either of an ethereal background to provide a standard of fixity in space, or of a uniformly-flowing river of time to provide a standard of speed. It became necessary to abandon the old scheme which had hitherto seemed to give an exact description of nature, and to introduce a new scheme as required by the experiments. In this new scheme, the phenomena of nature appeared as a picture painted in an entirely new space of four dimensions. This proved to be a purely mathematical and therefore probably a wholly fictitious space; in it the space and time of our everyday life are inextricably bound together into a new space of four dimensions, in which they then appear more or less as equal partners. There are innumerable ways in which space and time can be blended together to form such a space, but there is one specially simple way in which they can be

blended so that they figure as absolutely equal partners.

To be precise, there are four equal partners. The first three are the three dimensions of ordinary space—breadth, width and height, or, if we prefer to take a more geographical arrangement, north-south, east-west and up-down. The fourth is ordinary time measured in a way appropriate to the way in which we have measured our space (a year of time corresponding to a light-year of space, and so on), and then multiplied by the square-root of -1. This last multiplication by the square-root of -1 is of course the remarkable feature of the whole affair. For the square-root of -1 has no real existence; it is what the mathematician describes as an "imaginary" number. No real number can be multiplied by itself and give -1 as the product. Yet it is only when time is measured in terms of an imaginary unit of $\sqrt{(-1)}$ years that there is true equal partnership between space and time. This shews that the equal partnership is purely formal—it is nothing but a convenient fiction of the mathematician. Indeed, had it been anything more, our intuitive conviction that time is something essentially different from space could have had no basis in experience and so would have vanished ere now.

The discovery that nature treated space and time as equal partners, in the sense just explained, led to the conclusion that motion and change of motion no longer had any strict scientific meanings, and as a consequence the concept of force had to be discarded. Einstein, dismissing the appearance of force as a mere illusion, attributed the apparent curvatures in the paths of projectiles of all kinds to their efforts to keep a straight track through a space which was intrinsically curved. He then found it necessary to suppose that this curvature caused space ultimately

to bend back on itself like the earth's surface, so that the total volume of space became finite.

The general theory of relativity has long passed the stage of being regarded as an interesting speculation. It has accounted for phenomena of planetary motion which Newton's law of gravitation had entirely failed to explain—in particular the rotation in space of the elliptical orbit of the planet Mercury—and has also predicted other phenomena—the apparent displacements of stars near the sun at an eclipse, resulting from the light by which we see them being bent as it passes through the sun's gravitational field, and a certain displacement of stellar spectra towards the red end. These latter phenomena were entirely unsuspected when the predictions were first made, but have subsequently been fully confirmed by observation. Indeed, the theory has qualified as one of the ordinary working tools of astronomy. It has been used to measure the diameter of the small faint star Sirius B, the companion to Sirius (p. 285), as well as to test the nature of the stars at the centres of the "planetary nebulae" (p. 299).

On the other hand, its application to the universe as a whole does not stand on the same secure basis, with the result that several alternative views as to the structure of the universe have been, and still are, under consideration and discussion. We must review these in turn.

THE COSMOLOGY OF EINSTEIN. Einstein originally supposed that the dimensions of space were fixed by the amount of matter it contained, or again by the mean density of matter in space. We have no means of estimating how much matter may exist outside those regions of space which are within the reach of our telescopes, but within these regions matter seems to be fairly uniformly distributed in the form of extragalactic nebulae.

We have already seen (p. 79) how the weights of these vast bodies can be estimated, and we also know their average distances apart (p. 81). From these data, it appears that the mean density of matter in space must be about 10^{-30} times that of water. If the whole of space were filled with matter of this density, Einstein's original cosmology would fix the radius of space quite definitely at 32,000 million light-years, which is about 300 times the distance of the farthest visible nebula.

Nevertheless, the general theory of relativity did not lead up to this cosmology in a unique way. It was perfectly possible for the former to be true and the latter false. The general theory of relativity fixes the attributes of any small fraction of the universe quite definitely, but leaves open several alternative ways in which these small fractions can be pieced together to form a whole. Einstein's particular view of the cosmos could not therefore claim the prestige which attaches to his general theory of relativity as a whole. And indeed for some years it fell somewhat into disfavour, and appeared likely to be superseded by an alternative cosmology which de Sitter of Leiden propounded and developed in some detail in 1917.

THE COSMOLOGY OF DE SITTER. Let us first try to understand the essential differences between these two cosmologies.

Einstein's cosmology had supposed that the size of the cosmos was determined by the amount of matter it contained. If it had been decided, at the creation, to create a universe containing a certain amount of matter which was to obey certain natural laws, then space must at once have adjusted itself to the size suited for containing just this amount of matter and no more. Or, if the size of the universe and the natural laws were decided upon, the creation of a certain definite amount

of matter became an inevitable necessity. De Sitter's universe was less simple, or, if we prefer so to put it, allowed more freedom of choice in its creation. After the laws of nature had been fixed, it was still possible to make a universe of any size, and to put any amount of matter, within limits, into it. Looked at from the strictly scientific point of view, Einstein's universe had one element of arbitrariness fewer than de Sitter's universe, and to this extent it had the advantage of greater simplicity.

On the other hand, this simplicity was acquired at a price. The fundamental corner-stone of the whole theory of relativity is the equal partnership of space and time in the sense already explained. Einstein's cosmology had gained its simplicity only at the expense of supposing that this equality of partnership disappears when we view the cosmos as a whole. It supposed space and time to be indistinguishable (in the purely formal sense already indicated) only to a being whose experience is limited to a small fraction of the universe; they become utterly distinct for a being who can range through the whole of space and time. It is not altogether clear how much weight ought to be attached to this objection, if objection it is. Real space and real time undoubtedly are distinct. Even if we deny the reality of both, they still remain distinguishable as modes of perception. What reproach, then, could it be to a cosmology that it admits that, in the last resort, when the universe is contemplated on the grand scale, space and time resolve themselves into distinct types of entity? Somehow we knew it already, before ever we began to contemplate the universe on the grand scale.

Whatever the answer to this last question may be, de Sitter's cosmology avoided all possible reproach by maintaining a completely equal partnership of space

and time, not only in individual fractions of the cosmos, but throughout the cosmos as a whole. It will of course be understood that we are still speaking of equal partnership in the purely formal sense already explained, a light-year entering the cosmology on the same footing as the square-root of -1 years. Even de Sitter's cosmology did not pretend that a light-year (9·46 million million kilometres) was the same thing as twelve months.

Although Einstein's main theory of relativity has been amply confirmed by observation, the cosmological part of it did not predict any special features such as permitted of a direct observational test. De Sitter's cosmology, on the other hand, predicted that the spectra of all distant objects must shew a displacement towards the red, of amount depending on the distance of the object. The absolutely equal partnership of space and time is found to result in the vibrations of the light-waves emitted by any specified source being slower in distant than in near parts of the universe; the stream of time rolls more rapidly just where we happen to be than anywhere else. This sounds paradoxical at first, but examination shews that it is not; de Sitter was not asking us to return to a geocentric universe, because he shewed that the inhabitant of a distant star would also find that terrestrial atoms were keeping slower time than his own. The paradox is completely resolved by the concept of the relativity of all measures of space and time.

This displacement to the red as a result of mere distance is peculiar to de Sitter's cosmology. It is additional to the displacement which, as all cosmologies agree, the spectrum of a moving body must shew as the result of its motion, this latter being towards the red only if the body is receding from the earth (p. 56). On de Sitter's cosmology, the two displacements are

not entirely independent, for it is an essential feature of this cosmology that near bodies should tend to move farther apart from one another. Just as bits of straw thrown together into a stream tend to get separated as they float down the stream, so objects in de Sitter's universe move farther apart as they float down the stream of time.

THE EXPANDING UNIVERSE. It used to be thought that the cosmologies of Einstein and de Sitter were antagonistic to one another, since obviously no one universe could be an Einstein universe and a de Sitter universe at the same time.

Recent mathematical investigations by the Russian Friedmann (1922) and the Belgian Lemaître (1929) put a very different complexion on the matter. In brief, they shewed that the cosmological theories of Einstein and de Sitter were not so much antithetical as complementary to one another. For they proved that no universe could stay permanently in the state considered by Einstein. A universe in this state is an unstable structure; immediately it came into being it would start to expand, and would not cease from expanding until it had become a de Sitter universe. Even after this the expansion would continue, but it would now become identical with the normal expansion of the de Sitter universe, such as we have already considered.

In the light of these results, the problem of cosmology assumed a new form. The question at issue was no longer whether the actual universe was an Einstein universe or a de Sitter universe, but rather how far it had travelled along the road which begins with an Einstein universe and ends with a de Sitter universe.

It is clearly to observation that we must look for an answer. The fundamental characteristic of an Einstein universe is that space is static; it stands still, so that

the objects in it have no motion other than that which they have acquired from interaction with other bodies. On the other hand, the fundamental characteristic of the de Sitter universe is best explained by picturing space as expanding, with the result that every pair of objects in it continually increase their distance apart. Objects may have motions of their own, but superposed on to this they have a general motion, each away from all its neighbours, resulting from the expansion of space; they are like straws floating in a stream, and shewing the way in which its currents are flowing. This motion would be such that every object would recede from any single specified object—e.g. the earth—at a speed exactly proportional to its distance from that object.

Such a motion is characteristic not only of the de Sitter universe, but also of all the universes which are intermediate between those of Einstein and de Sitter. If then our actual universe occupies a position anywhere on this chain of theoretically possible universes, we might hope to detect such motions of recession by observational means. We should naturally look first to the most distant of known objects, the great extra-galactic nebulae, because if the motion occurs at all, it is here that we ought to find the highest speeds of recession.

The only way of estimating motion of recessions of astronomical bodies is by measuring the displacements of their spectral lines, as explained above (p. 56). The more distant of the extra-galactic nebulae are so faint that it has only recently become possible to study their spectra. These all shew displacements towards the red, indicating motions of recession. The speeds of motion are immense, the largest so far measured, that of an exceedingly faint nebula in the constellation Gemini, being 15,000 miles a second—a body travelling at this

speed would travel round the earth in less than two seconds. Corresponding displacements in the spectra of the nearer nebulae have been observed for some time, but these occur both towards the red and towards the violet ends of the spectrum, and so do not uniformly represent motions of recession. Although the majority of the nearer nebulae appear to be receding from us, a few, including those which are the nearest of all, are found to be approaching.

Examples of spectra of both types are shewn on Plate XVII (p. 96). In each case the central spectrum is that of the nebula, the upper and lower spectra (which are identical) forming a "comparison" spectrum (p. 56)—in this case the spectrum of helium. As these spectra are not easy to interpret, a key is provided at the bottom of the Plate. This shews only the position of the two lines *H* and *K* of calcium, all other lines and confusing details being omitted. The displacements are seen to be immense.

It is however clear that the displacements of the nebular spectra will not accurately represent the motions of the nebulae through space—they merely represent motion relative to our moving earth. And we have already seen that the rotation of the galaxy causes the sun to move round the centre of the galaxy with a speed of perhaps 140 miles a second; it is approaching these nebulae which lie in front of it and receding from those nebulae which lie behind it at this speed. We must allow for this motion in discussing the motions of the nebulae in space.

When this motion is duly taken into account, it is found that all known nebulae, except perhaps for a few insignificant exceptions, are receding from the centre of the galactic system with speeds which are almost exactly proportional to their distances from us, exactly as demanded by the theory of the expanding

universe. Dr Hubble and Dr Humason find a speed of recession of approximately 105 miles a second for each million light-years of distance.

Thus, observation clearly gives full support to the general theory of the expanding universe, and through this also to the general theory of relativity on which the more detailed theory is based. We find a general expansion which indicates that if the universe ever was in the stable Einstein configuration, it must have left it some time ago.

Yet observation cannot of itself tell us how far our universe has travelled along its path. Sir Arthur Eddington has recently tried to obtain a more definite answer to this problem by some brilliant, even if somewhat conjectural, theoretical researches, which we can best approach through a very simple analogy. When a grocer places a package of sugar on a spring balance, he will probably say he is weighing the sugar, but actually he is measuring the gravitational pull between the earth and the sugar—a pull in which the earth and the sugar enter in precisely similar capacities. If he were to fly around the solar system, taking his spring balance and package of sugar with him, he would find that the package had different weights on the different planets. On Jupiter it would weigh two-thirds as much as on the earth; on Mercury only a quarter as much, and so on. We could no longer say that the grocer was weighing the sugar; if we had to make a one-sided statement, it would be more accurate to say that he was weighing the planets. The full truth is that in any such measurement the weights of two bodies are always involved, and enter in a symmetrical way; if we know one weight, we can deduce the other, but if we know neither, it is a matter merely of our individual view-points whether we say we are weighing the one body or the other.

Certain well-known physical experiments are designed to weigh the smallest particles in the universe, namely the electrons, which enter into the composition of all matter (p. 121). Just as the measurement made with the spring balance involved the mass of the earth as well as that of the sugar, so Mach, Einstein and others have conjectured that the measurements made in experiments such as these involve both the mass of the particles and the mass of the whole universe. If so, it is a matter of choice whether the experimenter says he is measuring the one or the other, and it becomes possible to estimate the mass of the whole universe from these experiments, much as we can estimate the mass of the whole earth from the attraction it exerts on a pound of sugar. Eddington estimates it to be that of $1{\cdot}08 \times 10^{22}$ suns.

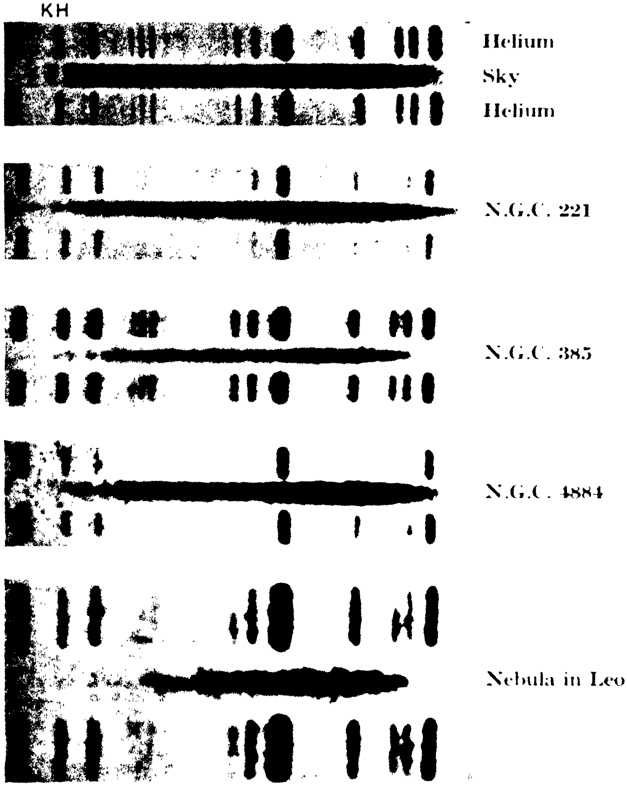
We have imagined the expanding universe to have started its existence as an Einstein universe in equilibrium, the whole of space being as full of matter as it could be. Calculation shews that an Einstein universe which contained the same amount of matter as $1{\cdot}08 \times 10^{22}$ suns would have a radius of 1068 million light-years. If, then, Eddington's theory is to be trusted, our universe must have started with this radius, and have been expanding ever since.

General mechanical theory shews that the speed of a falling object depends on the height from which the object has fallen. In a similar way, the speeds of the nebulae ought to depend on the extent to which the universe has expanded, or, more precisely, on the radius from which it started. Thus, if this universe had an original radius of 1068 million light-years, it ought to be possible to calculate the speeds of recession of the nebulae in terms of their distances. Eddington calculates velocities which are at least of the order of magnitude of those actually observed.

He accordingly supposes that the universe started as an Einstein universe, having a radius of 1068 million light-years, and that it contained an amount of matter equal to that of $1{\cdot}08 \times 10^{22}$ suns. If this matter were uniformly spread throughout the original universe, there would be about 10^{27} grammes to the cubic centimetre, which is perhaps about a thousand times greater than the present average density of matter. Thus, the mean density of the matter in the universe must have decreased about a thousand-fold since the universe started expanding. This is the same thing as saying that the linear dimensions of the universe have increased ten-fold, so that the present universe must have a radius of the order of 10,000 million light-years.

There are not, I think, many astronomers who have accepted the theories on which this estimate of Eddington's is based, and many have formed very different estimates of the size of the present universe. For instance, de Sitter, who has given much study to the question, is of opinion that the radius of the *present* universe is only of the order of 1000 million light-years, which is less even than Eddington's estimate for the radius of the original unexpanded Einstein universe.

On either of these estimates, or on any other which is at all reasonably probable, the part of space through which our telescopes can range forms only a tiny fraction of the whole of space—something like one part in a million. There is plenty of space still awaiting exploration. It is perhaps not surprising. Mankind, who has been possessed of telescopes for only 300 years out of the 300,000 of his residence on earth, could hardly hope to discover the whole of space in so short a time. Our astronomer explorers are moving from island to island in the small archipelago which surrounds their home in space, but they are still far from circum-



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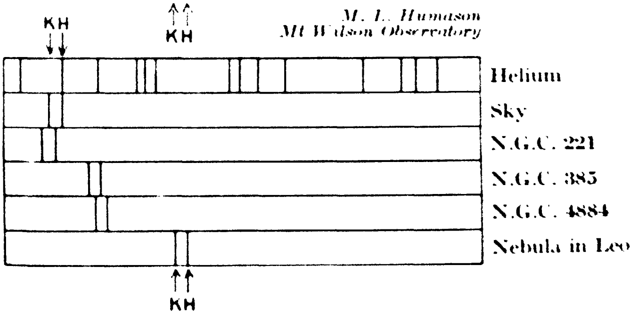


Nebular Spectra shewing Displacements

navigating the globe. And, just as the earliest geographers tried to estimate the size of the earth long before they thought of circumnavigating it, so astronomers are now trying to form estimates, which are necessarily vague, of the size of the whole universe from the properties of that part of it with which they are already acquainted. And we can well imagine that even the next generation will have completed the circumnavigation of space, and will think of a finite but unbounded space in the same way, and with the same ease, as we think of the finite but unbounded surface of the earth.

THE TIME SCALE

The agreement between the foregoing theories, which predict that the universe must be expanding, and observation, which indicates that the universe is actually expanding, is so unexpected, and so striking by its completeness, that it is difficult to hold one's enthusiasm in check. Yet it must be admitted there are very serious objections to the theories we have so far discussed, which at present seem to be quite fatal to them.

Quite apart from all theory, we have seen that observation reveals an apparent expansion at the speed of about 105 miles a second for every million light-years of distance. To put the same datum in another way, the universe appears to increase its dimensions one per cent. in every 20 million years. Now the theories we have discussed all require that this rate of expansion shall be approximately uniform, at least after the expansion has once got well under way. Thus, allowing for increase at "compound interest," the universe must double its dimensions every 1434 million years, and increase its dimensions eight-fold in 4300 million years. If, for instance, Eddington is right in thinking that the

whole increase has only been about ten-fold, then the main expansion must have taken place in the last 5000 million years or so. Even if we allow ten, or a thousand, or even a million, times the amount of expansion suggested by Eddington, we find that the main part of the expansion must all have occurred within the last 30,000 million years.

Something must no doubt be added for the time it took initially for the expansion to get under way, and it is exceedingly difficult to estimate how much to add. We have supposed that the original Einstein universe was unstable, just as a stick balanced on its point is unstable. Some small jar or irregularity starts the stick falling, and in the same way we must imagine that some small occurrence or disturbance started the universe expanding. We cannot calculate how long it takes for the fall of the stick to get well under way, until we know all the details of the disturbance which started the motion. In the same way, we cannot calculate how long it took for the expansion of the universe to get well under way until we have the corresponding information about the universe—and this we shall never know. Still, it is possible to calculate the time for various hypothetical disturbances. Calculations by Lemaître shew that the time in question can hardly have been more than about another 30,000 million years, so that it seems highly improbable that the total period can have exceeded 100,000 million years.

The difficulty to which we have referred arises from the fact that other means are available for estimating the total age of the universe. We shall discuss these in Chapter III and shall find that they indicate a total age of several millions of millions of years. The disparity between this and the 100,000 million years of expansion is too great to be bridged by adjustments of numerical

data; something must be definitely wrong somewhere.

This being so, it is significant that other theories of the expansion, or apparent expansion, of the universe are in the field beyond those already mentioned. It will be well to describe them briefly, and consider whether they hold out any hopes of a reconciliation between the two conflicting ages of the universe.

MILNE'S THEORY. In 1932 Professor A. E. Milne propounded a theory which has since, I think, been adequately proved to differ from those already discussed only in its mode of formulation. When a shell bursts on the field of battle, the various fragments travel at different rates, so that at any moment they are at different distances from the location of the original shell-burst. Those which are farthest away are of course travelling at the greatest speed, and in general the distance is exactly proportional to the speed of travel—which is exactly the law obeyed by the nebular velocities. Milne attempts to explain the nebular recessions in a somewhat similar manner, picturing the whole motion as taking place in an uncurved space which is precisely identical with the ordinary space of everyday experience.

In this way he obtains a picture which at first appears to be essentially different from the picture of Einstein and Lemaître we have just explained. But there is no reason why the same picture should not be drawn in many different ways, just as a map may be drawn on many different projections. We have already compared Einstein's conception of space to the curved surface of the earth. Now the earth's surface can be mapped out on a spherical surface—for instance, the ordinary globe of the geographical class-room—but it can also be mapped out on a flat surface, such as the ordinary Mercator or stereographic projections we find

in our atlases. Drs Kermack and McCrea have shewn, in brief, that Milne's description of the expanding universe bears the same relation to the Einstein-Lemaître description as does a Mercator projection to a globular map. As a result Milne's theory provides us with no new territory to explore; the physical phenomena of his theory must necessarily be precisely identical with those of the earlier Einstein-Lemaître theory. We are given two equally valid pictures of the phenomena, and there can be no possible means of deciding observationally between them.

The main value of Milne's work has perhaps proved to be something different from what he intended. It shews in how many ways the phenomena of nebular recession can be regarded, and leads us to reflect how little justification there can be for labelling any explanation as the "true" explanation. Incidentally we see how impossible it is to endow Einstein's curved space with any "physical reality" (whatever this may mean).

THE COSMICAL CONSTANT. Except for Milne's work, all the foregoing discussions of the universe have been based on the assumed existence of a "cosmical constant," a term which calls for some explanation.

We have seen how Einstein interpreted astronomical orbits as straight paths through a curved space. The orbits are most curved in the neighbourhood of massive bodies, so that it is clear that the curvature of space must be greatest near big masses of matter, as Einstein's theory implied. Thus we may say that these masses themselves produce a curvature of space.

Now Einstein very soon found that if space possessed no curvature beyond this, the universe would be unstable unless extremely complicated conditions were satisfied. To avoid this difficulty, he supposed space to have a further curvature inherent in its structure. This

curvature existed even when there were no massive bodies present, and was assumed to be uniform throughout space. Its amount—the same at every point of space and in every direction at each point—was measured by the "cosmical constant," which was thus a constant associated with the universe as a whole. If we again compare space to the earth's surface, the "cosmical constant" will give a measure of the quantity which corresponds to the radius of the earth, while the presence of massive bodies will produce minor local curvatures, like hills and valleys, molehills and rabbit-holes, on the earth's surface.

Einstein originally introduced this "cosmical constant" curvature because he saw no other means of obtaining a static universe; it was in the days before the general recession of the nebulae had been noticed. We now know that the universe is not static, so that Einstein's original reason for introducing the "cosmical constant" no longer exists. He and de Sitter have accordingly examined recently whether any other reasons remain which compel the retention of this "cosmical constant" and its associated curvature. They find none. The observed recessions of the nebulae are, they consider, consistent with the cosmical constant having any value whatever within certain assigned limits, including zero.

Subsequently, de Sitter has examined the consequences of attributing various values, including zero, to this constant. He finds that widening the possibilities in this way brings two new types of universe into the field beyond the expanding universe we have already described. There is a type of universe which begins life in an expanded form, contracts to a minimum and, after passing this minimum, continually expands without limit. There is also a type of universe—the "oscillating universe"—in which ex-

pansions and contractions succeed one another in regular alternation.

Now these two new types of universe have one significant feature in common. It is that their lives may go as far back into the past as we like; no cast iron limit is imposed on the lives of the stars. This is in itself a sufficient reason for preferring them to the original expanding universe of Lemaître. It does not of course compel us to pin our faith to either of them; there are still too many unexplored possibilities for a final decision to be possible. The essential point is that either of them seems capable, so far as we can at present judge, of allowing any length of life to the universe which astronomical data shew to be necessary.

Even so, we must not assume that we have completed the list of possibilities. The theory of relativity appears to be very firmly established as regards its applications to physics and to the astronomy of the solar system, but there is no such definiteness in its applications to the universe as a whole. It is still quite conceivable that some new formulation may be found, wider than the present or possibly contradictory to it, which may remove all difficulties about the time-scale in some entirely novel and unexpected way. The spectral displacements may, for instance, prove to be a mere effect of distance and may not indicate motions at all. This is not a mere fanciful flight, since we have seen (p. 90) that the original theory of de Sitter required precisely such a displacement as a result of distance alone. It was not of the kind needed for our present purpose since it was not proportional to the distance but to its square, and in any case it is probably too small to be observable. Still, it suggests a type of possibility which cannot be entirely excluded.

A MODEL OF THE UNIVERSE

We found it difficult enough to visualise the $4\frac{1}{4}$ light-years which constitute the distance to the nearest star, so we may be well advised not even to attempt to visualise the thousands of millions of light-years which now seem likely to constitute the circumference of the universe. Yet we may try to see all these distances in proper proportion relative to one another by the help of a model drawn to scale. We can escape the effort of trying to imagine unimaginably great distances by keeping the scale very small.

The earth, travelling 1200 times faster than an express train, makes a journey of 600 million miles around the sun every year. Let us represent this journey by a pin-head $\frac{1}{16}$ of an inch in diameter. This fixes the scale of our model; the sun has shrunk to a minute speck of dust $\frac{1}{3400}$ of an inch in diameter, while the earth is a still more minute speck which is too small to be seen at all even in the most powerful of microscopes. On this scale the nearest star in the sky, Proxima Centauri, must be placed about 225 yards away, and to contain even the hundred stars nearest to our sun in space, the model must be a mile high, a mile long and a mile wide.

Let us go on building the model. We may think of stars indiscriminately as specks of dust, because their sizes vary about as much as the sizes of specks of dust. In the vicinity of the sun we must place specks of dust at average distances of about a quarter of a mile apart. In other regions of space they are generally even farther apart, for, owing to the presence of the "local cluster," the immediate neighbourhood of the sun happens to be a rather crowded part of the sky. We go on building the model for hundreds of miles in every direction, and then, if we are building in a direction

well away from the galactic plane, the specks of dust begin to thin out; we are approaching the confines of the galaxy. In the galactic plane itself we build out for perhaps 5000 miles before we come to the farthest globular cluster, and we are still inside the galactic system. With our earth's long yearly journey round the sun as a pin-head, the whole galactic system is considerably larger than the continent of Asia. It may be well to pause and try to visualise the relative sizes of a pin-head and a continent before we go on with our mental model-building.

After we have finished the galactic system, we must travel at least 20,000 miles before we begin to set up the next bit of our model, at any rate if we are keeping it to scale. At this distance we place the next family of stars, a family which is probably substantially smaller and more compact than our own galactic family, but is comparable with it both in size and in numbers. So we go on building our model—a family of thousands of millions of stars every 30,000 miles or so—until we have two million such families. The model now stretches for about three million miles in every direction. This represents as far as we can see into space with our present telescopes. Beyond this we imagine the model going on in all directions, although not indefinitely; a journey of perhaps some hundreds of millions of miles in the model would bring us back to our starting point.

In this model, the sun is a very tiny speck of dust indeed—a speck less than a three-thousandth of an inch in diameter—while the other stars are other specks of dust, some larger, some smaller. The total number of specks of dust in our model is about comparable with the total number of specks of dust in the whole of London or New York—actually it is the number of dust particles in 3 cubic miles of air, with particles

occurring at the rate of a million to the cubic inch. Think of the sun as something less than a single speck of dust in a vast city, of the earth as less than a millionth part of such a speck of dust, and we have perhaps as vivid a picture as the mind can really grasp of the relation of our home in space to the rest of the universe.

An alternative procedure would have been to construct our scale-model by taking all the specks of dust in London and spreading them out to the right distances to represent the various stars in space. The average actual distances between specks of dust in London is a quite small fraction of an inch; to get our model to correct scale, this distance must be increased to about a quarter of a mile, even when we are building the part which represents the crowded part of space round the sun. If we build our model in this way, we obtain a vivid picture of the emptiness of space. Empty Waterloo Station of everything except six specks of dust, and it is still far more crowded with dust than space is with stars. This is true even of the comparatively crowded region inside the galactic system; it takes no account of the immense empty stretches between one system of stars and the next. On averaging throughout the whole of the model, the mean distance of a speck of dust from its nearest neighbour proves to be something like 80 miles. The universe consists in the main not of stars but of desolate emptiness—inconceivably vast stretches of desert space in which the presence of a star is a rare and exceptional event.

Let us in imagination take up a position in space somewhere near the sun, and watch the stars moving past with speeds about 1000 times that of an express train. If space were really crowded with stars, our position would be as unenviable as if we sat down in

the middle of Regent Street to watch the traffic go by —our life, though thrilling, would be brief. Yet, as exact calculation shews, the stellar traffic is so little crowded that we would have to wait about a million million million years before a star ran into us. Put in another form, the calculation shews that any one star may expect to move for something of the order of a million million million years before colliding with a second star. The stars move blindly through space, and the players in the stellar blind-man's-buff are so few and far between that the chance of encountering another star is almost negligible. We shall see later that this concept is of the profoundest significance in our interpretation of the universe.

CHAPTER II

Exploring the Atom

So far our exploration of the universe has been in the direction from man to bigger things than man; we have been exploring ranges of space which dwarf man and his home in space into utter insignificance. Yet we have explored only about half the total range of the universe; an almost equal range awaits exploration in the direction of the infinitely small. We appreciate only half of the infinite richness of the world around us until we extend our survey down to the smallest units of matter. This survey has been first the task, and now the brilliant achievement, of modern physics.

It may perhaps be asked why a book which attempts primarily to give an account of modern astronomy should concern itself with this other end of the universe. The answer is that the stars are something more than huge inert masses; they are machines in action, generating and emitting the radiation by which we see them. We shall best understand their mechanism by studying the ways in which radiation is generated and emitted on earth, and this takes us right into the heart of modern atomic physics. In the present book we naturally cannot attempt to cover the whole of this new field of knowledge; we shall concern ourselves only with those parts which are important for the interpretation of astronomical results.

ATOMIC THEORY

As far back as the fifth century before Christ, Greek philosophy was greatly exercised by the question of whether in the last resort the ultimate substance of

the universe was continuous or discontinuous. We stand on the sea-shore, and all around us see stretches of sand which appear at first to be continuous in structure, but which a closer examination shews to consist of separate hard particles or grains. In front rolls the ocean, which also appears at first to be continuous in structure, and this we find we cannot divide into grains or particles, no matter how we try. We can divide it into drops, but then each drop can be subdivided into smaller drops, and there seems to be no reason, on the face of things, why this process of subdivision should not be continued for ever. The question which agitated the Greek philosophers was, in effect, whether the water of the ocean or the sand of the seashore gave the truest picture of the ultimate structure of the substance of the universe.

The "atomic" school, founded by Democritus, Leucippus and Lucretius, believed in the ultimate discontinuity of matter; they taught that any substance, after it had been subdivided a sufficient number of times, would be found to consist of hard discrete particles which did not admit of further subdivision. For them the sand gave a better picture of ultimate structure than the water, because they thought that sufficient subdivision would cause the water to display the granular properties of sand. And this intuitional conjecture is amply confirmed by modern science.

The question is, in effect, settled as soon as a thin layer of a substance is found to shew qualities essentially different from those of a slightly thicker layer. A layer of yellow sand swept uniformly over a red floor will make the whole floor appear yellow if there is enough sand to make a layer at least one grain thick. If, however, there is only half this much sand, the redness of the floor inevitably shews through; it is impossible to spread sand in a uniform layer only half

a grain thick. This abrupt change in the properties of a layer of sand is of course a consequence of the granular structure of sand.

Similar changes are found to occur in the properties of thin layers of liquid. A teaspoonful of soup will cover the bottom of a soup plate, but a single drop of soup will only make an untidy splash. In some cases it is possible to measure the exact thickness of layer at which the properties of liquids begin to change. In 1890 Lord Rayleigh found that thin films of olive oil floating on water changed their properties entirely as soon as the thickness of the film was reduced to below a millionth of a millimetre (or a 25,000,000th part of an inch). The obvious interpretation, which is confirmed in innumerable ways, is that olive oil consists of discrete particles—analogous to the "grains" in a pile of sand—each having a diameter somewhere in the neighbourhood of a 25,000,000th part of an inch.

Every substance consists of such "grains"; they are called molecules. The familiar properties of matter are those of layers many molecules thick; the properties of layers less than a single molecule thick are known only to the physicist in his laboratory.

MOLECULES

How are we to break up a piece of substance into its ultimate grains, or molecules. It is easy for the scientist to say that, by subdividing water for long enough, we shall come to grains which cannot be subdivided any further; the plain man would like to see it done.

Fortunately the process is one of extreme simplicity. Take a glass of water, apply gentle heat underneath, and the water begins to evaporate. What does this mean? It means that the water is being broken up

into its separate ultimate grains or molecules. If the glass of water could be placed on a sufficiently sensitive spring balance, we should see that the process of evaporation does not proceed continuously, layer after layer, but jerkily, molecule by molecule. We should find the weight of the water changing by jumps, each jump representing the weight of a single molecule. The glass may contain any integral number of molecules but never fractional numbers—if fractions of a molecule exist, at any rate they do not come into play in the evaporation of a glass of water.

THE GASEOUS STATE. The molecules which break loose from the surface of the water as it evaporates form a gas—water-vapour or steam. A gas consists of a vast number of molecules which fly about entirely independently of one another, except at the rare instants at which two collide, and so interfere with each other's motion. The extent to which the molecules interfere with one another must obviously depend on their sizes; the larger they are, the more frequent their collisions will be, and the more they will interfere with one another's motion. Actually the extent of this interference provides the best means of estimating the sizes of molecules. They prove to be exceedingly small, being for the most part about a hundred-millionth of an inch in diamter, and, as a general rule, the simpler molecules have the smaller diameters, as we might perhaps have anticipated. The molecule of water has a diameter of 1·8 hundred-millionths of an inch ($4{\cdot}6 \times 10^{-8}$ cm.), while that of the simpler hydrogen molecule is only just over a hundred-millionth of an inch ($2{\cdot}7 \times 10^{-8}$ cm.). The fact that a number of different lines of investigation all assign the same diameters to these molecules provides an excellent proof of the reality of their existence.

As molecules are so exceedingly small, they must

also be exceedingly numerous. A pint of water contains $1{\cdot}89 \times 10^{25}$ molecules, each weighing $1{\cdot}06 \times 10^{-24}$ ounce. If these molecules were placed end to end, they would form a chain capable of encircling the earth over 200 million times. If they were scattered over the whole land surface of the earth, there would be nearly 100 million molecules to every square inch of land. If we think of the molecules as tiny seeds, the total amount of seed needed to sow the whole earth at the rate of 100 million molecules to the square inch could be put into a pint pot.

These molecules move with very high speeds; the molecules which constitute the ordinary air of an ordinary room move with an average speed of about 500 yards a second. This is roughly the speed of a rifle-bullet, and is rather more than the ordinary speed of sound. As we are familiar with this latter speed from everyday experience, it is easy to form some conception of molecular speeds in a gas. It is not a mere accident that molecular speeds are comparable with the speed of sound. Sound is a disturbance which one molecule passes on to another when it collides with it, rather like relays of messengers passing a message on to one another, or Greek torch-bearers handing on their lights. Between collisions the message is carried forward at exactly the speed at which the molecules travel. If these all travelled with precisely the same speed and in precisely the same direction, the sound would of course travel with just the speed of the molecules. But many of them travel on oblique courses, so that although the average speed of individual molecules in ordinary air is about 500 yards a second, the net forward velocity of the sound is only about 370 yards a second.

At high temperatures the molecules may have even greater speeds; the molecules of steam in a boiler may move at 1000 yards a second.

It is the high speed of molecular motion that is responsible for the great pressure exerted by a gas; any surface in contact with ordinary air is exposed to a hail of molecules each moving with the speed of a rifle-bullet. With each breath we take, swarms of millions of millions of millions of molecules enter our bodies, each moving at about 500 yards a second, and nothing but their incessant hammering on the walls of our lungs keeps our chests from collapsing. To take another instance, the piston in a locomotive cylinder is bombarded by about 14×10^{28} molecules every second, each moving at about 800 yards a second. This incessant fusillade of innumerable tiny bullets urges the piston forward in the cylinder, and so propels the train.

Perhaps the best general mental picture we can form of a gas is that of an incessant hail of shot or rifle-bullets flying indiscriminately in all directions, and running into one another at frequent intervals. In ordinary air each molecule collides with some other molecule about 3000 million times every second, and travels an average distance of about $\frac{1}{160,000}$ inch between successive collisions. If we compress a gas to a greater density, more molecules are crowded into a given space, so that collisions become more frequent and the molecules travel shorter distances between collisions. If, on the contrary, we reduce the pressure of the gas, and so lessen its density, collisions become less frequent and the distance of travel of a molecule between successive collisions—the "free-path" as it is called—is increased. In the lowest vacua which are at present obtainable in the laboratory, a molecule can travel over 100 yards without colliding with any other molecule, although there are still 600,000 million molecules to the cubic inch.

Under astronomical conditions still lower vacua may occur. In some nebulae molecules of gas may travel

millions of miles without a collision, so few are the molecules to a given volume of space.

It might be thought that the flying molecules would soon be brought to rest by their collisions; rifle-bullets undoubtedly would, but not the molecule bullets of a gas, for reasons now to be explained.

ENERGY. The amount of the charge of powder used to fire a rifle-bullet gives a measure of the "energy of motion" which is imparted to the bullet. To fire a bullet of double weight at the same speed requires twice as much powder, because the energy of motion of a bullet, or indeed of any other moving object, is proportional to its weight. But to fire the same bullet with double speed does not merely require double the charge of powder. Four times as much powder is needed, because the energy of motion of a moving body is proportional to the *square* of its speed. The experienced motorist is familiar with this; if our brakes stop our car in 20 feet when we are travelling 20 miles an hour, they will not stop it in 40 feet when travelling at 40 miles an hour; we need 80 feet. Double speed requires four times the distance to pull up in, because double speed represents fourfold energy of motion. In general, the energy of motion of any moving body whatever is proportional both to the weight of the body and to the square of its speed*.

One of the great achievements of nineteenth-century physics was to establish the general principle known as the "conservation of energy." Energy can exist in

* This is expressed in the mathematical formula $\frac{1}{2}mv^2$ for the energy of motion of a body of weight m moving with a speed v. If m is measured in grammes, and v in centimetres per second, the energy of motion of the body is said to be $\frac{1}{2}mv^2$ "ergs." Thus an "erg" is the energy of motion of a body of 2 grammes weight (so that $\frac{1}{2}m = 1$) moving with a speed of one centimetre a second. As an example, the energy of an express train of 300 tons' weight (3×10^8 gms.) moving at 60 miles an hour (2682 cms. a second) is 1079×10^{14} ergs; a cannon-ball or shell weighing a ton and moving at 1520 feet a second has precisely the same energy.

a number of forms, and can change about almost endlessly from one form to another, but it can never be utterly destroyed. The energy of a moving body is not lost when the body is brought to rest, it merely takes some other form. When a bullet is brought to rest by hitting a target, part of its energy of motion goes into heating up the target, and part into heating up, or perhaps even melting, the bullet. In its new guise of heat, there is just as much energy as there was in the original motion of the bullet.

In accordance with the same principle, energy cannot be created; all existing energy must have existed from all time, although possibly in some form entirely different from its present form. For instance, gunpowder contains a large amount of energy stored up in the form of chemical energy; we have to take precautions to prevent this bottled-up energy suddenly breaking free and doing damage, as, for instance, by exploding the vessel in which it is contained, kicking things up into the air, and so forth. A rifle is in effect a device for setting free the energy contained in a measured charge of gunpowder, and directing as much as possible of it into the form of energy of motion of a bullet. When we fire a bullet at a target, a specified amount of energy (determined by the charge of powder we have used) is transformed from chemical energy, residing in the powder, first into energy of motion, residing in the bullet (and to a minor degree in the recoil of the rifle), and then finally into heat-energy, residing partly in the spent bullet and partly in the target. Here we have energy taking three different forms in rapid succession. All the life of the universe may be regarded as manifestations of energy masquerading in various forms, and all the changes in the universe as energy running about from one of these forms to the other, but always without altering its

total amount. Such is the great law of conservation of energy.

Among the commoner forms of energy may be mentioned electric energy, as exemplified by the energy of a charged accumulator or of a thundercloud; mechanical energy, as exemplified in the coiled spring of a watch or the raised weight of a clock; chemical energy, as exemplified by the energy stored up in gunpowder or in coal, wood and oil; energy of motion, as exemplified by the motion of a bullet, and finally heat-energy, which, as we have seen, is exemplified by the heat which appears when the motion of a rifle-bullet is checked.

HEAT. Let us examine further into heat as a possible form of energy. When we want to warm a room, we light a fire and set free some of the chemical energy which is stored up in coal or wood, or we turn on an electric heater and let the electric current transport to us some of the energy which is being set free by the burning of coal in a distant power-station. But what, in the last resort, is heat, and how does it come to be a mode of energy?

Heat, whether of a gas, a liquid or a solid, is merely the energy of motion of individual molecules. When we heat up the air of a room we simply make its molecules move faster, and the total heat of the substance is the total energy of all the molecules of which it is composed. In pumping up a bicycle tyre, we drive the piston of the pump forward in opposition to the impact of innumerable millions of molecules of air inside the pump. In kicking the opposing molecules out of its way, the piston increases their speed of motion. The resulting increase in the energy of motion of the molecules is simply an increase of heat. We could verify this by inserting a thermometer, or, still more simply, by putting our hand on the pump; it feels hot.

The molecules of a solid are not possessed of much energy, and so do not move very fast—so slowly indeed that they seldom change their relative positions, the neighbouring molecules gripping them so firmly that their feeble energy of motion cannot extricate them. If we warm the solid up, the molecules acquire more energy, and so begin to move faster. After a time they are moving with such speeds that they can laugh at the restraining pulls from their neighbours; each molecule has enough energy of motion to go where it pleases, and we have a crowd of molecules moving freely as independent units, jostling one another and pushing their way past one another; the substance has assumed the liquid state. To make the picture definite, ice has melted and become water; the frozen grip is relaxed, and the molecules flow freely past one another. Each still exerts forces on its neighbours, but these are no longer strong enough to preclude all motion. Heat the liquid further, thus further increasing the energy of motion of the molecules, and these begin to break loose entirely from their bonds and fly about freely in space forming a gas or vapour. If we go on supplying heat, the whole substance will in time assume the gaseous state. Heating the gas still further now causes the molecule-bullets to fly still faster; it increases their energy of motion.

The average energy of motion of the molecules in a gas is proportional to the temperature of the gas—indeed, this is the way in which temperature is defined. The temperature must not, however, be measured on the Fahrenheit or Centigrade scale in ordinary use, but on what is called the "absolute" scale, which has its zero at $-273°$ Centigrade, or $-469°$ Fahrenheit. This "absolute" zero, being the temperature of a body which has no further heat to lose, is the lowest temperature possible. We can approach to within a small

fraction of one degree of it in the laboratory, and find that it freezes air, hydrogen and even helium, the most refractory gas of all, solid. A thermometer placed out in interstellar space, far from any star, would probably shew a temperature of only about four degrees above absolute zero, while still lower temperatures must be reached out beyond the limits of the galactic system.

MOLECULAR COLLISIONS. We may now try to picture a collision between two molecule-bullets in a gas. Two lead bullets colliding on a battlefield would probably change most of their energy of motion into heat-energy; they would become hotter, or perchance even melt. But how can the molecule-bullets transform their energy of motion into heat-energy? For them heat and energy of motion are not two different forms of energy, they are one and the same thing; their heat is their energy of motion. The total energy must be conserved, and there is no new disguise that it can assume. So it comes about that when two molecule-bullets collide, the most that can happen is that they may exchange a certain amount of energy of motion. If their energies of motion before collision were, say 7 and 5 respectively, their energies after collision may be 6 and 6, or 8 and 4, or 9 and 3, or any other combination which adds up to 12.

It is the same at every collision; energy can neither be lost nor transformed, and so the bullets on the molecular battlefield go on flying for ever, happily hitting only one another, and doing no harm to one another when they hit. Their energies of motion go up and down, down and up, according as they make lucky hits or the reverse, but the most they have to fear are fluctuations and never total loss of energy; their motion is perpetual.

ATOMS

In the gaseous state, each separate molecule retains all the chemical properties of the solid or liquid substance from which it originated; molecules of steam, for instance, moisten salt or sugar, or combine with thirsty substances such as unslaked lime or potassium chloride, just as water does.

Is it possible to break up the molecules still further? Lucretius and his predecessors would, of course, have said: "No." A simple experiment, which, however, was quite beyond their range, will speedily shew that they were wrong.

On sliding the two wires of an ordinary electric bell circuit into a tumbler of water, down opposite sides, bubbles of gas will be found to collect on the wires, and chemical examination shews that the two lots of gas have entirely different properties. They cannot, then, both be water-vapour, and in point of fact neither of them is; one proves to be hydrogen and the other oxygen. There is found to be twice as much hydrogen as oxygen, whence we conclude that the electric current has broken up each molecule of water into two parts of hydrogen and one of oxygen. These smaller units into which a molecule is broken are called "atoms." Each molecule of water consists of two atoms of hydrogen (H) and one atom of oxygen (O); this is expressed in its chemical formula H_2O.

All the innumerable substances which occur on earth—shoes, ships, sealing-wax, cabbages, kings, carpenters, walruses, oysters, everything we can think of—can be analysed into their constituent atoms, either in this or in other ways. It might be thought that a quite incredible number of different kinds of atoms would emerge from the rich variety of substances we find on earth. Actually the number is quite small. The same

atoms turn up again and again, and the great variety of substances we find on earth results, not from any great variety of atoms entering into their composition, but from the great variety of ways in which a few types of atoms can be combined—just as in a colour-print three colours can be combined so as to form almost all the colours we meet in nature, not to mention other weird hues such as never were on land or sea.

Analysis of all known terrestrial substances has, so far, revealed only 90 different kinds of atoms. Probably 92 exist, there being reasons for thinking that two, or possibly even more, still remain to be discovered. Even of the 90 already known, the majority are exceedingly rare, most common substances being formed out of the combinations of about 14 different atoms, say hydrogen (H), carbon (C), nitrogen (N), oxygen (O), sodium (Na), magnesium (Mg), aluminium (Al), silicon (Si), phosphorus (P), sulphur (S), chlorine (Cl), potassium (K), calcium (Ca), and iron (Fe).

In this way, the whole earth, with its endless diversity of substances, is found to be a building built of standard bricks—the atoms. And of these only a few types, about 14, occur at all abundantly in the structure, the others appearing but rarely.

SPECTROSCOPY. Just as a bell struck with a hammer emits a characteristic note, so every atom put in a flame or in an electric arc or discharge-tube, emits a characteristic light, which the spectroscope will resolve into its separate constituents.

We have already seen how the spectrum of sunlight discloses the chemical composition of the solar atmosphere, and here again we still find the same types of atoms as on earth, and no others. With a few quite unimportant exceptions, every line in the sun's spectrum can be identified as originating from some

type of atom already known on earth. We have already given a list of the fifteen metals which are believed to be commonest in the sun's atmosphere. The first seven, which account for no less than 96 per cent. of the whole, have already figured in our list of the fourteen elements which are commonest on earth. Actually they are precisely the seven principal constituents of terrestrial rocks, although their relative proportions are different on the sun and earth.

Thus, broadly speaking the same atoms occur in the sun's atmosphere as on earth, and we have already seen that the same is true of the atmospheres of the stars. It is tempting to jump to the generalisation that the whole universe is built solely of the 90 or 92 types of atoms found on earth, but at present there is no justification for this. The light we receive from the sun and stars comes only from the outermost layers of their surfaces, and so conveys no information at all as to the types of atoms to be found in the stars' interiors. Indeed we have no knowledge of the types of atoms which occur in the interior of our own earth.

THE STRUCTURE OF THE ATOM. Until quite recently, atoms were regarded as the permanent bricks of which the whole universe was built. All the changes of the universe were supposed to amount to nothing more drastic than a re-arrangement of permanent indestructible atoms; like a child's box of bricks, these built many buildings in turn. The story of twentieth-century physics is primarily the story of the shattering of this concept.

It was towards the end of the last century that Crookes, Lenard, and above all, Sir J. J. Thomson first began to break up the atom. The structures which had been deemed the unbreakable bricks of the universe for more than 2000 years, were suddenly shown to be very susceptible to having fragments chipped off.

A mile-stone was reached in 1897, when Thomson shewed that these fragments were identical no matter what type of atom they came from; they were of equal weight and they carried equal charges of negative electricity. On account of this last property they were called "electrons." The atom cannot, however, be built up of electrons and nothing else, for as each electron carries a negative charge of electricity, a structure which consisted of nothing but electrons would also carry a negative charge. Two negative charges of electricity repel one another, as also do two positive charges, while two charges, one of positive and one of negative electricity, attract one another. This makes it easy to determine whether any body or structure carries a positive or a negative charge of electricity, or no charge at all. Observation shews that a complete atom carries no charge at all, so that somewhere in the atom there must be a positive charge of electricity, of amount just sufficient to neutralise the combined negative charges of all the electrons.

In 1911 experiments by Sir Ernest Rutherford and others revealed the architecture of the atom, in its main lines at least. As we shall soon see (p. 126 below), nature herself provides an endless supply of small particles charged with positive electricity, and moving with very high speeds, in the α-particles shot off from radio-active substances. Rutherford's method was in brief to fire these into atoms and observe the result. And the surprising result he obtained was that the vast majority of these bullets passed straight through the atom as though it simply did not exist. It was like shooting at a ghost.

Yet the atom was not all ghostly. A tiny fraction—perhaps one in 10,000—of the bullets were deflected from their courses as if they had met something very substantial indeed. A mathematical calculation shewed

that these obstacles could only be the missing positive charges of the atoms.

A detailed study of the paths of these projectiles proved that the whole positive charge of an atom must be concentrated in a single very small space, having dimensions of the order of only a millionth of a millionth of an inch. In this way, Rutherford was led to propound the view of atomic structure which is generally associated with his name. He supposed the chemical properties and nature of the atom to reside in a weighty, but excessively minute, central "nucleus" carrying a positive charge of electricity, around which a number of negatively charged electrons described orbits. He had to suppose that the electrons were in motion in the atom, otherwise the attraction of positive for negative electricity would immediately draw them into the central nucleus—just as gravitational attraction would cause the earth to fall into the sun, were it not for the earth's orbital motion. In brief, Rutherford supposed the atom to be constructed like the solar system, the heavy central nucleus playing the part of the sun and the electrons acting the parts of the planets.

The modern theory of wave-mechanics casts doubt on some at least of these concepts—perhaps on all, although this is still in doubt. Thus it may prove necessary to discard many or all of them before long. Yet Rutherford's concepts provide a simple and easily visualised picture of the atom, whereas the theory of wave-mechanics has not yet been able to provide a picture at all. For this reason we shall continue to describe the atom in terms of Rutherford's picture, and its subsequent extension by Bohr and others.

According to this picture, the electrons are supposed to move round the nucleus with just the speeds necessary to save them from being drawn into it, and these

speeds prove to be terrific, the average electron revolving around its nucleus several thousand million million times every second, with a speed of hundreds of miles a second. Thus the smallness of their orbits does not prevent the electrons moving with higher orbital speeds than the planets, or even the stars themselves.

By clearing a space around the central nucleus, and so preventing other atoms from coming too near to it, these electronic orbits give size to the atom. The volume of space kept clear by the electrons is enormously greater than the total volume of the electrons; roughly, the ratio of volumes is that of the battlefield to the bullets. The atom, with a radius of about 2×10^{-8} cm., has about 100,000 times the diameter, and so about a thousand million million times the volume, of a single electron, which has a radius of only about 2×10^{-13} cm. The nucleus, although it generally weighs 3000 or 4000 times as much as all the electrons in the atom together, is at most comparable in size with, and may be even smaller than, a single electron.

We have already commented on the extreme emptiness of astronomical space. Choose a point in space at random, and the odds against its being occupied by a star are enormous. Even the solar system consists overwhelmingly of empty space; choose a spot inside the solar system at random, and there are still immense odds against its being occupied by a planet or even by a comet, meteorite or smaller body. And now we see that this emptiness extends also to the space of physics. Even inside the atom we choose a point at random, and the odds against there being anything there are immense; they are of the order of at least millions of millions to one. We saw how six specks of dust inside Waterloo Station represented—or rather over-represented—the extent to which space was

crowded with stars. In the same way a few wasps—six for the atom of carbon—flying around in Waterloo Station will represent the extent to which the atom is crowded with electrons—all the rest is emptiness. As we pass the whole structure of the universe under review, from the giant nebulae and the vast interstellar and internebular spaces down to the tiny structure of the atom, little but vacant space passes before our mental gaze. We live in a gossamer universe; pattern, plan and design are there in abundance, but solid substance is rare.

ATOMIC NUMBERS. The number of electrons which fly round in orbits in an atom is called the "atomic number" of the atom. Atoms of all atomic numbers from 1 to 92 have been found, except for two missing numbers 85 and 87. As already mentioned, it is highly probable that these also exist, and that there are 92 "elements" whose atomic numbers occupy the whole range of atomic numbers from 1 to 92 continuously.

The atom of atomic number unity is of course the simplest of all. It is the hydrogen atom, in which a solitary electron revolves around a nucleus whose charge of positive electricity is exactly equal in amount, although opposite in sign, to the charge on the negative electron.

Next comes the helium atom of atomic number 2, in which two electrons revolve about a nucleus which has four times the weight of the hydrogen nucleus, although carrying only twice its electric charge. After this comes the lithium atom of atomic number 3, in which three electrons revolve around a nucleus having six times the weight of the hydrogen atom and three times its charge. And so it goes on, until we reach uranium, the heaviest of all atoms known on earth, which has 92 electrons describing orbits about a nucleus of 238 times the weight of the hydrogen nucleus.

RADIO-ACTIVITY

While physical science was still engaged in breaking up the atom into its component factors, it made the further discovery that the nuclei themselves were neither permanent nor indestructible. In 1896 Becquerel had found that various substances containing uranium possessed the remarkable property, as it then appeared, of spontaneously affecting photographic plates in their vicinity. This observation led to the discovery of a new property of matter, namely radio-activity. All the results obtained from the study of radio-activity in the few following years were co-ordinated in the hypothesis of "spontaneous disintegration" which Rutherford and Soddy advanced in 1903. According to this hypothesis in its present form, radio-activity indicates a spontaneous break-up of the nuclei of the atoms of radio-active substances. These atoms are so far from being permanent and indestructible that their very nuclei crumble away with the mere lapse of time, so that what was once the nucleus of a uranium atom is transformed, after sufficient time, into the nucleus of a lead atom.

The process of transformation is not instantaneous; it proceeds gradually and by distinct stages. During its progress, three types of product are emitted, which are designated α-rays, β-rays, and γ-rays.

These were originally described indiscriminately as rays because all three were found to have the power of penetrating through a certain thickness of air, metal, or other substance. It was not until later that their true nature was discovered. It is well known that magnetic forces, such as, for instance, occur in the space between the poles of a magnet, cause a moving particle charged with electricity to deviate from a straight course; the particle deviates in one direction or the other according

as it is charged with positive or negative electricity. On passing the various rays emitted by radio-active substances through the space between the poles of a powerful magnet, the α-rays were found to consist of particles charged with positive electricity, and the β-rays to consist of particles charged with negative electricity. But the most powerful magnetic forces which could be employed failed to cause the slightest deviation in the paths of the γ-rays, from which it was concluded that either the γ-rays were not material particles at all, or that, if they were, they carried no electric charges. The former of these alternatives was subsequently proved to be the true one.

α-PARTICLES. The positively charged particles which constitute α-rays are generally described as α-particles. In 1909 Rutherford and Royds allowed α-particles to penetrate through a thin glass wall of less than a hundredth of a millimetre thickness into a chamber from which they could not escape—a sort of mouse-trap for α-particles. After the process had continued for a long time, the final result was not an accumulation of α-particles but an accumulation of the gas helium, the next simplest gas after hydrogen. In this way it was established that the positively charged α-particles are simply nuclei of helium atoms; the α-particles, being positively charged, had attracted negatively charged electrons to themselves out of the walls of the chamber and the result was a collection of complete helium atoms.

The α-particles move with enormous speeds, which depend upon the nature of the radio-active substance from which they have been shot out. The fastest particles of all, those emitted by Thorium C′, move with a speed of 12,800 miles a second; even the slowest, those from Uranium 1, have a speed of 8800 miles a second, which is about 30,000 times the ordinary mole-

cular velocity in air. Particles moving with such speeds as these knock all ordinary molecules out of their way; this explains the great penetrating power of the α-rays.

β-PARTICLES. By examining the extent to which their motion was influenced by magnetic forces, the β-rays were found to consist of negatively charged electrons, exactly similar to those which surround the nucleus in all atoms. As an α-particle carries a positive charge equal in amount to that of two electrons, an atom which has ejected an α-particle is left with a deficiency of positive charge, or what comes to the same thing, with a negative charge, equal to that of two electrons. Consequently it is natural, and indeed almost inevitable, that the ejections of α-particles should alternate with an ejection of negatively charged electrons, in the proportion of one α-particle to two electrons, so that the balance of positive and negative electricity in the atom may be maintained. The β-particles move with even greater speeds than the α-particles, many approaching to within a few per cent. of the velocity of light (186,000 miles a second).

One of the most beautiful devices known to physical science, the invention of Professor C. T. R. Wilson, makes it possible to study the motions of the α- and β-particles as they thread their way through a gas, colliding with its molecules on their way. A chamber through which the particles can be made to travel is filled with water-vapour in such a condition that the passage of an electrically charged particle leaves behind it a trail of condensations which can be photographed. As an example, Plate XVIII (p. 128) shews a photograph taken by Professor Wilson himself, in which the trails of both α- and β-particles appear on the same plate. The four straight thick lines are tracks of α-particles; the curved and much fainter lines are tracks of β-particles. As the α-particles weigh nearly 7400 times as much as the

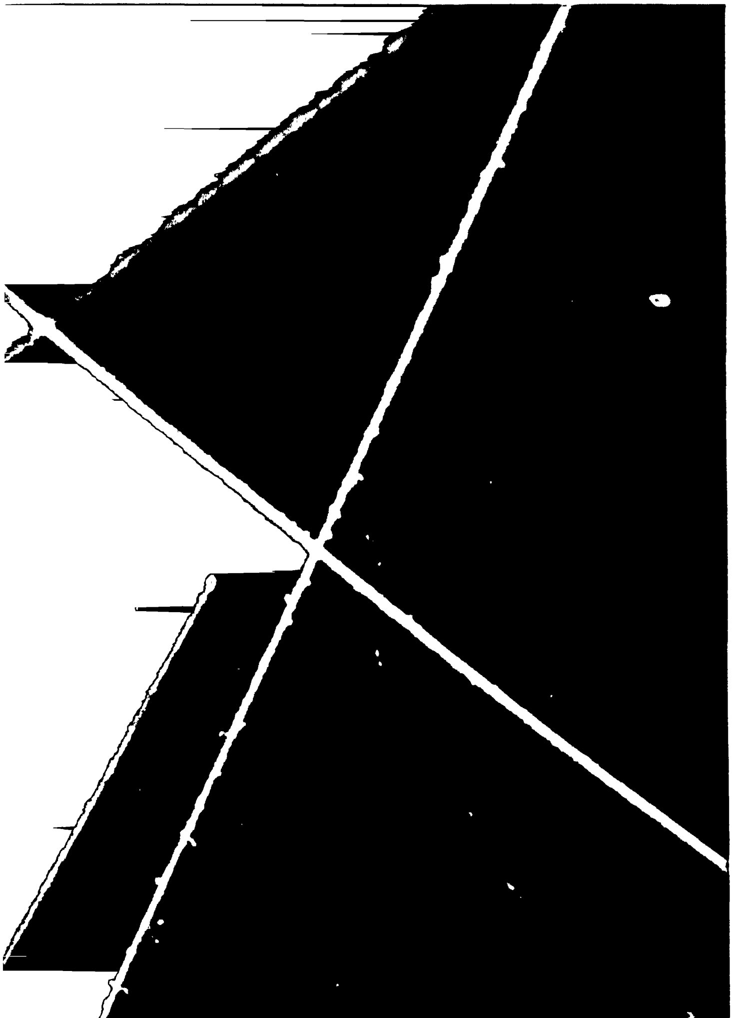
β-particles, they naturally create more disturbance in the gas, and so leave broader and more pronounced tracks; also they pursue a comparatively straight course while the lighter β-particles are deflected from their courses by many of the molecules they meet. The knobby-looking excrescences which may be seen emerging from both sides of the longest of the α-ray tracks are of interest; they represent the short paths of electrons knocked out of atoms by the passage of the α-particle.

γ-RAYS. As has already been mentioned, the γ-rays are not material particles at all; they prove to be merely radiation of a very special kind, which we shall discuss below (p. 138).

Thus the break-up of a radio-active atom may be compared to the discharge of a gun; the α-particle is the shot fired, the β-particles are the smoke, and the γ-rays are the flash. The atom of lead which finally remains is the unloaded gun, and the original radio-active atom, of uranium or what not, was the loaded gun. And the special peculiarity of radio-active guns is that they go off spontaneously and of their own accord. All attempts to pull the trigger have so far failed, or at least have led to inconclusive results; we can only wait, and the gun will be found to fire itself in time.

ATOMIC NUCLEI

With the unimportant exceptions of potassium and rubidium (of atomic numbers 19 and 37), the property of radio-activity occurs only in the most complex and massive of atoms, being indeed confined to those of atomic numbers above 83. Yet, although the lighter atoms are not liable to spontaneous disintegration in the same way as the heavy radio-active atoms, their nuclei are of composite structure, and can be broken



C. T. R. Wilson

The tracks of α- and β-particles

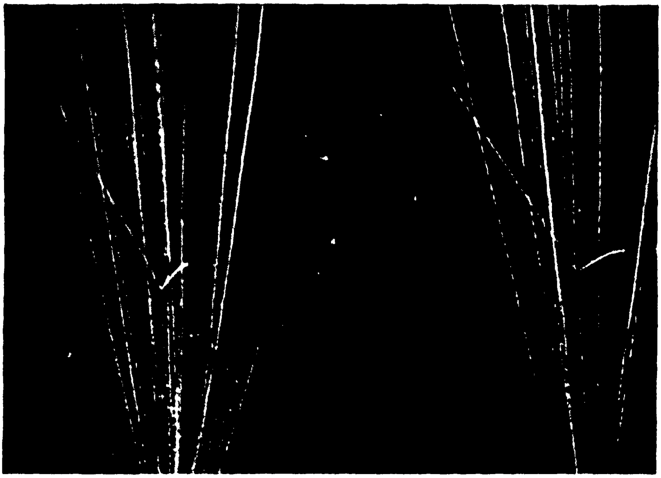


Fig. 1

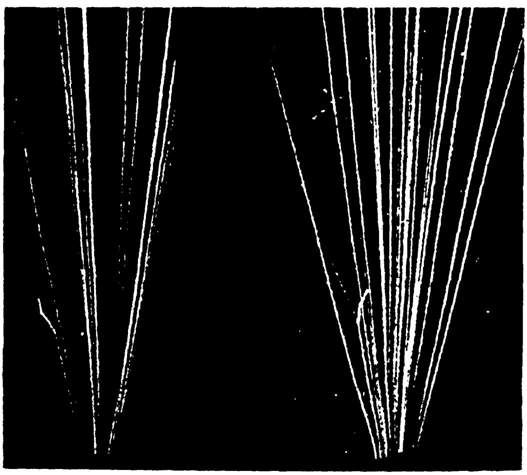


Fig. 2

P. M. S. Blackett

Collisions of α-particles with Nitrogen Atoms

In fig. 1 the α-particle merely rebounds from a nitrogen atom. In fig. 2 it drives out a proton and then joins itself to the atom

up by artificial means. In 1920 Rutherford, using radio-active atoms as guns, fired α-particles at light atoms and found that direct hits broke up their nuclei. There is, however, found to be a significant difference between the spontaneous disintegration of the heavy radio-active atoms and the artificial disintegration of the light atoms; in the former case, apart from the ever-present β-rays and γ-rays, only α-particles are ejected, while in the latter case α-particles were not ejected at all, but particles of only about a quarter their weight, which proved to be identical with the nuclei of hydrogen atoms.

These sensational events in the atomic underworld can be photographed by Professor C. T. R. Wilson's condensation method already explained. Plate XIX shews two collisions of an α-particle with a nitrogen atom photographed by Mr P. M. S. Blackett. The straight lines are merely the quite uneventful tracks of ordinary α-particles similar to those already shewn in Plate XVIII. But one α-particle track in each photograph suddenly branches, so that the complete figure is of a Y-shape.

There is little room for doubt that in fig. 1 the branch occurs because the α-particle has collided with a nitrogen atom; the stem of the Y is the track of the α-particle before the collision; the two upper branches are the tracks of the α-particle and the nitrogen atom after the collision, the latter now moving with enormous speed and hitting everything out of its way. By taking simultaneous photographs in two directions at right angles, as shewn in the Plate, Mr Blackett was able to reconstruct the whole collision, and the angles were found to agree exactly with those which dynamical theory would require on this interpretation of the photograph.

The occurrence photographed in fig. 2 is of a different

type, since exact measurement shews that the angles are not those which dynamical theory would require if the upper branches of the Y were the tracks of the α-particles and the nitrogen atom as in fig. 1. The stem of the Y is still an ordinary α-particle track, but the long faint upper branch is the track of something less massive than an α-particle, namely a particle of only a quarter the weight of an α-particle which has been shot out of the nucleus, whilst the shorter and clearer branch is that of the nitrogen atom moving along in company with the α-particle, which it has captured. It would take too much space to describe in full the beautiful method by which Blackett has established this interpretation of his photographs, but there is little room for doubt that in fig. 2 he has succeeded in photographing the break-up of the nucleus of an atom of nitrogen.

ISOTOPES. Two atoms have the same chemical properties if the charges of positive electricity carried by their nuclei are the same. The amount of this charge fixes the number of electrons which can revolve around the nucleus, this number being of course exactly that needed to neutralise the electric field of the nucleus, and this in turn fixes the atomic number of the element (p. 124). And it has for long been known that the weights of all atoms are, to a very close approximation, multiples of a single definite weight. This unit weight is approximately equal to the weight of the hydrogen atom, but is more nearly equal to a sixteenth of the weight of the oxygen atom. The weight of any type of atom, measured in terms of this unit, is called the "atomic weight" of the atom.

It used to be thought that a mass of any single chemical element, such as mercury or xenon, consisted of entirely similar atoms, every one of which had not only the same atomic number but also the same atomic

weight. But Dr Aston has recently shewn very convincingly that atoms of the same chemical element, say neon or chlorine, may have nuclei of a great many different weights. The various forms which the atoms of the same chemical element can assume are known as isotopes, being of course distinguished by their different weights.

These weights are much nearer to whole numbers than were the old "atomic" weights of the chemists. For instance the atomic weight of chlorine used to be given as 35·5, and this was taken to mean that chlorine consisted of a mixture of atoms each 35·5 times as massive as the hydrogen atom. Aston finds that chlorine consists of a mixture of atoms of atomic weights 35 and 37 (or more accurately 34·983 and 36·980), the former being approximately three times as plentiful as the latter. In the same way a mass of mercury, of which the mean atomic weight is about 200·6, is found to be a mixture of seven kinds of atoms of atomic weights 196, 198, 199, 200, 201, 202, 204. Tin is a mixture of no fewer than eleven isotopes—112, 114, 115, 116, 117, 118, 119, 120, 121, 122, 124.

PROTONS AND ELECTRONS. When the presence of isotopes is taken into account, the atomic weights of all atoms prove to be far nearer to integral numbers than had originally been thought. This, in conjunction with Rutherford's artificial disintegration of atomic nuclei, led to the general acceptance of the hypothesis that the whole universe is built up of only two kinds of ultimate bricks, namely, electrons and protons. Each proton carries a positive charge of electricity exactly equal in amount to the negative charge carried by an electron, but has about 1847 times the weight of the electron. Protons are supposed to be identical with the nucleus of the hydrogen atom, all other nuclei being composite structures in which both protons and

electrons are closely packed together. For instance, the nucleus of the helium atom, the α-particle, consists of four protons and two electrons, these giving it approximately four times the weight of the hydrogen atom, and a resultant charge equal to twice that of the nucleus of the hydrogen atom.

NEUTRONS. Until quite recently this hypothesis was believed to give a satisfactory and complete account of the structure of matter. Then in 1931 two German physicists, Bothe and Becker, bombarding the light elements beryllium and boron with the very rapid α-particles emitted by polonium, obtained a new and very penetrating radiation which they were at first inclined to interpret as a kind of γ-radiation. Subsequently Dr Chadwick of Cambridge shewed that it possessed properties which were inconstant with this interpretation and made it clear that the radiation consists of material objects of a type hitherto unknown to science. To the greatest accuracy of which the experiments permit, these objects are found to have the same mass as the hydrogen atom, while their very high penetrating power shews that if they have any electric charge at all, it can only be a minute fraction at most of the charge of the electron.

Thus it seems likely that the radiation consists of *uncharged particles* of the same mass as the proton—something quite new in a world which until recently was believed to consist entirely of charged particles. Chadwick describes these new particles as "neutrons." Whether they are themselves fundamental constituents of matter or not remains to be seen. Chadwick has suggested that they may be composite structures, each consisting of a proton and electron in such close combination that they penetrate matter almost as freely as though they had no size at all. On the other hand Heisenberg has considered the possibility

that the neutron may be fundamental, the nucleus of an atom being built up solely of positively charged protons and uncharged neutrons, while the negative electrons are confined to the regions outside the nucleus. On this view there are just as many protons in the nucleus as there are electrons outside the nucleus, the number of each being the atomic number of the element, while the excess of mass needed to make up the atomic weight is provided by the inclusion of the requisite number of neutrons in the nucleus. Isotopes of the same element differ of course merely in having different numbers of neutrons in their nuclei.

Rutherford and other physicists have considered the further possibility that other kinds of neutrons, with double the mass of the hydrogen atom, may also occur in atomic nuclei, a hypothesis for which there seems to be considerable observational support.

POSITIVE ELECTRONS. Even more revolutionary discoveries were to come. A few years ago it seemed a piece of extraordinary good luck that in the α-particles nature herself had provided projectiles of sufficient shattering power to smash up the nucleus of the atom and disclose its secrets to the observation of the physicist. More recently nature has been found to provide yet more shattering projectiles in the cosmic radiation (p. 161) which continually bombards the surface of the earth—probably from outer space. This radiation has such a devastating effect on the atomic nuclei that it is difficult to make much of the resulting collection of fragments. It is, however, always possible to examine any *débris*, no matter how involved, by noticing how the constituent particles move when acted on by magnetic forces.

In 1932 C. D. Anderson made observations which suggested that this *débris* contained, among other ingredients, particles having the same positive charge as

the proton, but a mass only comparable with, and possibly equal to, that of the electron. The existence of such particles has recently (February 1933) been confirmed by Blackett and Occhialini at Cambridge. The new particles may well be described as positively charged electrons, and so have been named "positrons."

As these new particles are believed to emerge from atomic nuclei, it would seem plausible to suppose that they must be normal constituents of the nuclei. Yet the recent discovery of the neutron suggests other possibilities.

We have already mentioned the hypothesis, advocated by Heisenberg and others, that the nucleus consists solely of neutrons and protons. Anderson has suggested that the proton may not be a fundamental unit in the structure of matter, but may consist of a positron and a neutron in combination. Every nucleus would then contain only neutrons and positrons, and the positrons could be driven out by bombardment in the ordinary way.

The objection to this view is that the *débris* of the nuclei shattered by cosmic radiation is found to contain electrons as well as positrons, the electrons emerging, so far as can be seen, from the same atomic nuclei as the positrons. This has led Blackett and Occhialini to propound the alternative hypothesis that the electrons and positrons are born in pairs as the result of the processes of bombardment and disintegration of atomic nuclei. At first this may seem a flagrant violation of all our views as to the permanence of matter, but we shall see shortly that it is entirely in accord with the present trend of physics.

It seems fairly certain that the positron has at most but a temporary existence. For positrons do not appear to be associated with matter under normal conditions, although they ought to abound if they were being con-

tinually produced out of nuclei at anything like the rate which the observations of Blackett and Occhialini seem to indicate. They might of course rapidly disappear from view through entering into combination with negatively charged particles to form some sort of permanent stable structure, but it seems more probable, as Blackett and Occhialini themselves suggest, that they disappear from existence altogether by combining with negative electrons. Just as a pair of electrons—one positively charged and one negatively charged—can be born out of nothing but energy, so they can die in one another's arms and leave nothing but energy behind. We shall discuss the underlying physical mechanism almost immediately.

Before the existence of the positron had been observed, or even suspected experimentally, Professor Dirac of Cambridge had propounded a mathematical theory which predicted not only the existence of the positron, but also the way in which it ought to behave. Dirac's theory is too abstrusely mathematical to be explained here, but it predicts that a shower of positrons ought gradually to fade away by spontaneous combination with negative electrons, following the same law of decay as radio-active substances. And the average life of a positron is predicted to be one of only a few millionths of a second, which amply explains why the positron can live long enough to be photographed in a condensation chamber, but not long enough to shew its presence elsewhere in the universe.

RADIATION

We have so far discussed only the material constituents of matter: we have pictured the atom as being built up of some or all of the material ingredients which we have described as electrons, protons, neutrons and positrons.

Yet this is not the whole story. If it were, every atom would consist of a certain number of protons and neutrons with just sufficient electrons and positrons to make the total electric charge equal to zero. Thus, apart from the insignificant weights of electrons and positrons, the weight of every atom would be an exact multiple of the weight of a hydrogen atom. Experiment shews this not to be the case.

ELECTROMAGNETIC ENERGY. To get at the whole truth, we have to recognise that, in addition to containing material electrons and protons, with possible neutrons and positrons, the atom contains yet a further ingredient which we may describe as electromagnetic energy. We may think of this, although with something short of absolute scientific accuracy, as bottled radiation.

If we disturb the surface of a pond with a stick, a series of ripples starts from the stick and travels, in a series of ever-expanding circles, over the surface of the pond. As the water resists the motion of the stick, we have to work to keep the pond in a state of agitation. The energy of this work is transformed, in part at least, into the energy of the ripples. We can see that the ripples carry energy about with them, because they cause a floating cork or a toy boat to rise up against the earth's gravitational pull. Thus the ripples provide a mechanism for distributing over the surface of the pond the energy that we put into the pond through the medium of the moving stick.

Light and all other forms of radiation are analogous to water-ripples or waves, in that they distribute energy from a central source. The sun's radiation distributes through space the vast amount of energy which is generated inside the sun. We hardly know whether there is any actual wave-motion in light or not, but we know that both light and all other types

of radiation are propagated in such a form that they have many of the properties of a succession of waves.

We have seen how the different colours of light which in combination constitute sunlight can be separated out by passing the light through a prism, thus forming a rainbow or "spectrum" of colours. The separation can also be effected by an alternative instrument, the diffraction grating, which consists merely of a metal mirror with a large number of parallel lines scratched evenly across its surface. The theory of the action of this latter instrument is well understood; it shews that actually the light is separated into waves of different wave-lengths*. This proves that different colours of light are produced by waves of different lengths, and at the same time enables us to measure the lengths of the waves which correspond to the different colours of light.

These prove to be very minute. The reddest light we can see, which is that of longest wave-length, has a wave-length of only $\frac{3}{100,000}$ inch ($7{\cdot}5 \times 10^{-5}$ cm.); the most violet light we can see has a wave-length only half of this, or 0·000015 inch. Light of all colours travels with the same uniform speed of 186,000 miles, or 3×10^{10} centimetres, a second. The number of waves of red light which pass any fixed point in a second is accordingly no fewer than four hundred million million. This is called the "frequency" of the light. Violet light has the still higher frequency of eight hundred million million; when we see violet light, eight hundred million million waves of light enter our eyes each second.

The spectrum of analysed sunlight appears to the eye to stretch from red light at one end to violet light at the other, but these are not its true limits. When

* The wave-length in a system of ripples is the distance from the crest of one ripple to that of the next, and the term may be applied to all phenomena of an undulatory nature.

certain chemical salts are placed beyond the violet end of the visible spectrum, they are found to shine vividly, shewing that even out here energy is being transported, although in invisible form. And other methods make it clear that the same is true out beyond the red end of the spectrum. A thermometer, or other heat-measuring instrument, placed here will shew that energy is being received here in the form of heat.

In this way we find that regions of invisible radiation stretch indefinitely from both ends of the visible spectrum. From one end—the red—we can pass continuously to waves of the type used for wireless transmission, which have wave-lengths of the order of hundreds, or even thousands, of yards. From the violet end, we pass through waves of shorter and ever shorter wave-length—all the various forms of ultra-violet radiation. At wave-lengths of from about a hundredth to a thousandth of the wave-length of visible light, we come to the familiar X-rays, which penetrate through inches of our flesh, so that we can photograph the bones inside. Far out even beyond these, we come to the type of radiation which constitutes the γ-rays, its wave-length being of the order of $\frac{1}{10,000,000,000}$ inch, or only about a hundred-thousandth part of the wave-length of visible light. Thus the γ-rays may be regarded as invisible radiation of extremely short wave-length. We shall discuss the exact function they serve later. For the moment let us merely remark that in the first instance they served the extremely useful function of fogging Becquerel's photographic plates, thus leading to the detection of the radio-active property of matter.

It is a commonplace of modern electromagnetic theory that energy of every kind carries weight about with it, weight which is in every sense as real as the weight of a ton of coal. A ray of light causes an impact on any surface on which it falls, just as a

jet of water does, or a blast of wind, or the fall of a ton of coal; with a sufficiently strong light one could knock a man down just as surely as with the jet of water from a fire-hose. This is not a mere theoretical speculation. The pressure of light on a surface has been both detected and measured by direct experiment. The experiments are extraordinarily difficult because, judged by all ordinary standards, the weight carried by radiation is exceedingly small; all the radiation emitted from a 50 horse-power searchlight working continuously for a century weighs only about a twentieth of an ounce.

It follows that any substance which is emitting radiation must at the same time be losing weight. In particular, the disintegration of any radio-active substance must involve a decrease of weight, since it is accompanied by the emission of radiation in the form of γ-rays. The ultimate fate of an ounce of uranium may be expressed by the equation:

$$1 \text{ ounce uranium} = \begin{cases} 0{\cdot}8653 \text{ ounce lead,} \\ 0{\cdot}1345 \quad \text{,,} \quad \text{helium,} \\ 0{\cdot}0002 \quad \text{,,} \quad \text{radiation.} \end{cases}$$

The lead and helium together contain just as many electrons and just as many protons as did the original ounce of uranium, but their combined weight is short of the weight of the original uranium by about one part in 4000. Where 4000 ounces of matter originally existed, only 3999 now remain; the missing ounce has gone off in the form of radiation.

This makes it clear that we must not expect the weights of the various atoms to be exact multiples of the weight of the hydrogen atom; any such expectation would ignore the weight of the bottled-up electromagnetic energy which is capable of being set free and going off into space in the form of radiation as the atom changes its make up. The weight of this energy

is relatively small, so that the weights of the atoms must be expected to be approximately, although not exactly, integral multiples of that of the hydrogen atom, and this expectation is confirmed. The exact weight of our atomic building is not simply the total weight of all its bricks; something must be added for the weight of the mortar—the electromagnetic energy —which keeps the bricks bound together.

Thus the normal atom consists of its material constituents—protons, electrons, neutrons and positrons, or some at least of these—and also of energy, which also contributes something to its weight. When the atom re-arranges itself, either spontaneously or under bombardment, protons and electrons, or other fragments of its material structure, may be shot off in the form of α- and β-particles, and energy may also be set free in the form of radiation. This radiation may either take the form of γ-rays, or, as we shall shortly see, of other forms of visible and invisible radiation. The final weight of the atom will be obtained by deducting from its original weight not only the weight of all the ejected electrons and protons, but also the weight of all the energy which has been set free as radiation.

QUANTUM THEORY

The series of concepts which we now approach are difficult to grasp and still more difficult to explain, largely, no doubt, because our minds receive no assistance from our everyday experience of nature*. It becomes necessary to speak mainly in terms of analogies, parables and models which can make no claim to represent ultimate reality; indeed, it is rash

* The reader whose interest is limited to astronomy may prefer to proceed at once to Chapter III.

to hazard a guess even as to the direction in which ultimate reality lies.

The laws of electricity which were in vogue up to about the end of the nineteenth century—the famous laws of Maxwell and Faraday—required that the energy of an atom should continually decrease, through the atom scattering energy abroad in the form of radiation, and so having less and less left for itself. These same laws predicted that all energy set free in space should rapidly transform itself into radiation of almost infinitesimal wave-length. Yet these things simply did not happen, making it obvious that the then prevailing electrodynamical laws had to be given up.

CAVITY-RADIATION. A crucial case of failure was provided by what is known as "cavity-radiation." A body with a cavity in its interior is heated up to incandescence; no notice is taken of the light and heat emitted by its outer surface, but the light imprisoned in the internal cavity is let out through a small window and analysed into its constituent colours by a spectroscope or diffraction grating. This is the radiation that is known as "cavity-radiation." It represents the most complete form of radiation possible, radiation from which no colour is missing, and in which every colour figures at its full strength. No known substance ever emits quite such complete radiation from its surface, although many approximate to doing so. We speak of such bodies as "full radiators."

The nineteenth-century laws of electromagnetism predicted that the whole of the radiation emitted by a full radiator or from a cavity ought to be found at or beyond the extreme violet end of the spectrum, independently of the precise temperature to which the body had been heated. In actual fact the radiation is usually found piled up at exactly the opposite end

of the spectrum, and in no case does it ever conform to the predictions of the nineteenth-century laws, or even begin to think of doing so.

In the year 1900 Professor Planck of Berlin discovered experimentally the law by which cavity-radiation is distributed among the different colours of the spectrum. He further shewed how his newly-discovered law could be deduced theoretically from a system of electromagnetic laws which differed very sensationally from those then in vogue.

Planck imagined all kinds of radiation to be emitted by systems of vibrators which emitted light when excited, much as tuning forks emit sound when they are struck. The old electrodynamical laws predicted that each vibration should gradually come to rest and then stop, as the vibrations of a tuning fork do, until the vibrator was in some way excited again. Rejecting all this, Planck supposed that a vibrator could change its energy by sudden jerks, and in no other way; it might have one, two, three, four or any other integral number of units of energy, but no intermediate fractional numbers, so that gradual changes of energy were rendered impossible. The vibrator, so to speak, kept no small change, and could only pay out its energy a shilling at a time until it had none left. Not only so, but it refused to receive small change, although it was prepared to accept complete shillings. This concept, sensational, revolutionary and even ridiculous, as many thought it at the time, was found to lead exactly to the distribution of colours actually observed in cavity-radiation.

In 1917 Einstein put the concept into the more precise form which now prevails. According to a theory previously advanced by Professor Niels Bohr of Copenhagen, an atomic or molecular structure does not change its configuration, or dissipate away its energy,

by gradual stages; on the contrary, the changes are so abrupt that it is almost permissible to regard them as a series of sudden jumps or jerks. Bohr supposed that an atomic structure has a number of possible states or configurations which are entirely distinct and detached one from another, just as a weight placed on a staircase has only a possible number of positions; it may be 3 stairs up, or 4 or 5, but cannot be 3¼ or 3¾ stairs up. The change from one position to another is generally effected through the medium of radiation. The system can be pushed upstairs by absorbing energy from radiation which falls on it, or may move downstairs to a state of lower energy and emit energy in the form of radiation in so doing. Only radiation of a certain definite colour, and so of a certain precise wave-length, is of any account for effecting a particular change of state. The problem of shifting an atomic system is like that of extracting a box of matches from a penny-in-the-slot machine; it can only be done by a special implement, to wit a penny, which must be of precisely the right size and weight—a coin which is either too small *or too large*, too light *or too heavy*, is doomed to fail. If we pour radiation of the wrong wave-length on to an atom, we may reproduce the comedy of the millionaire whose total wealth will not procure him a box of matches because he has not a loose penny, or we may reproduce the tragedy of the child who cannot obtain a slab of chocolate because its hoarded wealth consists of farthings and half-pence, but we shall not disturb the atom. When mixed radiation is poured on to a collection of atoms, these absorb the radiation of just those wave-lengths which are needed to change their internal states, and none other; radiation of all other wave-lengths passes by unaffected.

This selective action of the atom on radiation is put

in evidence in a variety of ways; it is perhaps most simply shewn in the spectra of the sun and stars. Dark lines similar to those which Fraunhofer observed in the solar spectrum are observed in the spectra of practically all stars (see Plate IX, p. 55), and we can now understand why this must be. Light of every possible wave-length streams out from the hot interior of a star, and bombards the atoms which form its atmosphere. Each atom drinks up that radiation which is of precisely the right wave-length for it, but has no interaction of any kind with the rest, so that the radiation which is finally emitted from the star is deficient in just the particular wave-lengths which suit the atoms. Thus the star shews an *absorption spectrum* of fine lines. The positions of these lines in the spectrum shew what types of radiation the stellar atoms have swallowed, and so enable us to identify the atoms from our laboratory knowledge of the tastes of different kinds of atoms for radiation. But what ultimately decides which types of radiation an atom will swallow, and which it will reject?

It had been part of Planck's theory that radiation of each wave-length has associated with it a certain amount of energy, called the "quantum," which depends on the wave-length and on nothing else. The quantum is supposed to be proportional to the "frequency" (p. 137), or number of vibrations of the radiation per second*, and so is *inversely* proportional to the wave-length of the radiation—the shorter the wave-length, the greater the energy of the quantum, and conversely. Red light has feeble quanta, violet light has energetic quanta, and so on.

* To be precise, if ν is the frequency of the radiation, its quantum of energy is $h\nu$, where h is a universal constant of nature, known as Planck's constant. This constant is of the physical nature of energy multiplied by time; its numerical value is:

$$6{\cdot}55 \times 10^{-27} \text{ erg} \times \text{second.}$$

Einstein now supposed that radiation of a given type could effect an atomic or molecular change, only if the energy needed for the change is precisely equal to that of a single quantum of the radiation. This is commonly known as Einstein's law; it determines the precise type of radiation needed to work any atomic or molecular penny-in-the-slot mechanism*.

We notice that work which demands one powerful quantum cannot be performed by two, or indeed by any number whatever, of feeble quanta. A small amount of violet (high-frequency) light can accomplish what no amount of red (low-frequency) light can effect.

The law prohibits the killing of two birds with one stone, as well as the killing of one bird with two stones; the whole quantum is used up in effecting the change, so that no energy from this particular quantum is left over to contribute to any further change. This aspect of the matter is illustrated by Einstein's photochemical law: "in any chemical reaction which is produced by the incidence of light, the number of molecules which are affected is equal to the number of quanta of light which are absorbed." Those who manage penny-in-the-slot machines are familiar with a similar law: "the number of articles sold is exactly equal to the number of coins in the machine."

If we think of energy in terms of its capacity for doing damage, we see that radiation of short wave-length can work more destruction in atomic structures than radiation of long wave-length—a circumstance with which every photographer is painfully familiar; we can admit as much red light as we please without any damage being done, but even the tiniest gleam of

* In the form of an equation:

$$E_1 - E_2 = h\nu,$$

where E_1, E_2 are the energies of the material system before and after the change, ν is the frequency of the radiation, and h is Planck's constant already specified.

violet light spoils our plates. Radiation of sufficiently short wave-length may not only rearrange molecules or atoms; it may break up any atom on which it happens to fall, by shooting out one of its electrons, giving rise to what is known as photoelectric action. Again there is a definite limit of frequency, such that light whose frequency is below this limit does not produce any effect at all, no matter how intense it may be; whereas as soon as we pass to frequencies above this limit, light of even the feeblest intensity starts photoelectric action at once. Again the absorption of one quantum breaks up only one atom, and further ejects only one electron from the atom. If the radiation has a frequency above this limit, so that its quantum has more energy than the minimum necessary to remove a single electron from the atom, the whole quantum is still absorbed, the excess energy now being used in endowing the ejected electron with motion.

ELECTRON ORBITS. These concepts are based upon Bohr's supposition that only a limited number of orbits are open to the electrons in an atom, all others being prohibited for reasons which Bohr's theory did not fully explain, and that an electron is free to move from one permitted orbit to another under the stimulus of radiation. Bohr himself investigated the way in which the various permitted orbits are arranged. Modern investigations indicate the need for a good deal of revision of his simple concepts, but we shall discuss these in some detail, partly because Bohr's picture of the atom still provides the best working mechanical model we have, and partly because an understanding of his simple theory is absolutely essential to the understanding of the far more intricate theories which are beginning to replace it.

The hydrogen atom, as we have already seen, consists of a single proton as central nucleus, with a single

electron revolving around it. The nucleus, with about 1847 times the weight of the electron, stands practically at rest unagitated by the motion of the latter, just as the sun remains practically undisturbed by the motion of the earth round it. The nucleus and electron carry charges of positive and negative electricity, and therefore attract one another; this is why the electron describes an orbit instead of flying off in a straight line, again like the earth and sun. Furthermore, the attraction between electric charges of opposite sign, positive and negative, follows, as it happens, precisely the same law as gravitation, the attraction falling off as the inverse square of the distance between the two charges. Thus the nucleus-electron system is similar in all respects to a sun-planet system, and the orbits which an electron can describe around a central nucleus are precisely identical with those which a planet can describe about a central sun; they consist of a system of ellipses each having the nucleus in one focus (p. 48).

Yet the general concepts of quantum-dynamics prohibit the electron from moving in all these orbits indiscriminately. Bohr's original theory supposed that the electron in the hydrogen atom could move only in certain circular orbits whose diameters were proportional to the squares of the natural numbers, and so to 1, 4, 9, 16, 25,.... Bohr subsequently modified this very simple hypothesis, and the theory of wave-mechanics has recently modified it much further.

Yet it still remains true that the hydrogen atom has always very approximately the same energy as it would have if the electron were describing one or another of these simple orbits of Bohr. Thus, when its energy changes, it changes as though the electron jumped over from one to another of these orbits. For this reason it is easy to calculate what changes of energy a hydrogen atom can experience—they are precisely

those which correspond to the passage from one Bohr orbit to another. For example, the two orbits of smallest diameters in the hydrogen atom differ in energy by 16×10^{-12} erg. If we pour radiation of the appropriate wave-length on to an atom in which the electron is describing the smallest orbit of all, it crosses over to the next orbit, absorbing 16×10^{-12} erg of energy in the process, and so becoming temporarily a reservoir of energy holding 16×10^{-12} erg. If the atom is in any way disturbed from outside, it may of course discharge the energy at any time, or it may absorb still more energy and so increase its store.

If we know all the orbits which are possible for an atom of any type, it is easy to calculate the changes of energy involved in the various transitions between them. As each transition absorbs or releases exactly one quantum of energy, we can immediately deduce the frequencies of the light emitted or absorbed in these transitions. In brief, given the arrangement of atomic orbits, we can calculate the spectrum of the atom. In practice the problem of course takes the converse form: given the spectrum, to find the structure of the atom which emits it. Bohr's model of the hydrogen atom is a good model at least to this extent—that the spectrum it would emit reproduces the hydrogen spectrum almost exactly. Yet the agreement is not quite perfect, and for this reason it is now generally accepted that Bohr's scheme of orbits is inadequate to account for actual spectra. We continue to discuss Bohr's scheme, not because the atom is actually built that way, but because it provides a working model which is good enough for our present purpose.

An essential, although at first sight somewhat unexpected, feature of the whole theory is that even if the hydrogen atom charged with its 16×10^{-12} erg

of energy is left entirely undisturbed, the electron must, after a certain time, lapse back spontaneously to its original smaller orbit, ejecting its 16×10^{-12} erg of energy in the form of radiation in so doing. Einstein shewed that, if this were not so, then Planck's well-established "cavity-radiation" law could not be true. Thus, a collection of hydrogen atoms in which the electrons describe orbits larger than the smallest possible orbit is similar to a collection of uranium or other radio-active atoms, in that the atoms spontaneously fall back to their states of lower energy as the result merely of the passage of time.

The electron orbits in more complicated atoms have much the same general arrangement as in the hydrogen atom, but are different in size. In the hydrogen atom the electron normally falls, after sufficient time, to the orbit of lowest energy and stays there. It might be thought by analogy that in more complicated atoms in which several electrons are describing orbits, all the electrons would in time fall into the orbit of lowest energy and stay there. Such does not prove to be the case. There is never room for more than one electron in the same orbit. This is a special aspect of a general principle which appears to dominate the whole of physics. It has a name—"the exclusion-principle"—but this is about all as yet; we have hardly begun to understand it. In another of its special aspects it becomes identical with the old familiar corner-stone of science which asserts that two different pieces of matter cannot occupy the same space at the same time. Without understanding the underlying principle, we can accept the fact that two electrons not only cannot occupy the same space, but cannot even occupy the same orbit. It is as though in some way the electron spread itself out so as to occupy the whole of its orbit, thus leaving room for no other. No doubt this must

not be accepted as a literal picture of things, and yet the modern theory of wave-mechanics suggests that in some sense (which we cannot yet specify with much precision) the orbits of lowest energy in the hydrogen atom are possible orbits just because the electron can completely fill them, and that adjacent orbits are impossible because the electron would fill them $\frac{3}{4}$ or $1\frac{1}{2}$ times over, and similarly for more complicated atoms. In this connection it is perhaps significant that no single known phenomenon of physics makes it possible to say that at a given instant an electron is at such or such a point in an orbit of lowest energy; such a statement appears to be quite meaningless and the condition of an atom is apparently specified with all possible precision by saying that at a given instant an electron is in such an orbit, as it would be, for instance, if the electron had spread itself out into a ring. We cannot say the same of other orbits. As we pass to orbits of higher energy, and so of greater diameter, the indeterminateness gradually assumes a different form, and finally becomes of but little importance. Whatever form the electron may assume while it is describing a little orbit near the nucleus, by the time it is describing a very big orbit far out it has become a plain material particle charged with electricity.

Thus, whatever the reason may be, electrons which are describing orbits in the same atom must all be in different orbits. The electrons in their orbits are like men on a ladder; just as no two men can stand on the same rung, so no two electrons can ever follow one another round in the same orbit. The neon atom, for instance, with 10 electrons is in its normal state of lowest energy when its 10 electrons each occupy one of the 10 orbits whose energy is lowest. For reasons which the quantum theory has at last succeeded in elucidating, there are, in every atom, two orbits in

which the energy is equal and lower than in any other orbit. After this come eight orbits of equal but substantially higher energy, then 18 orbits of equal but still higher energy, and so on. As the electrons in each of these various groups of orbits all have equal energy, they are commonly spoken of, in a graphic but misleading phraseology, as rings of electrons. They are designated the K-ring, the L-ring, the M-ring and so on. The K-ring, which is nearest to the nucleus, has room for two electrons only. Any further electrons are pushed out into the L-ring, which has room for eight electrons, all describing orbits which are different but of equal energy. If still more electrons remain to be accommodated, they must go into the M-ring and so on.

In its normal state, the hydrogen atom has one electron in its K-ring, while the helium atom has two, the L, M, and higher rings being unoccupied. The atom of next higher complexity, the lithium atom, has three electrons, and as only two can be accommodated in its K-ring, one has to wander round in the outer spaces of the L-ring. In beryllium with four electrons, two are driven out into the L-ring. And so it goes on, until we reach neon with 10 electrons, by which time the L-ring as well as the inner K-ring is full up. In the next atom, sodium, one of the 11 electrons is driven out into the still more remote M-ring, and so on. Provided the electrons are not being excited by radiation or other stimulus, each atom sinks in time to a state in which its electrons are occupying its orbits of lowest energy, one in each.

So far as our experience goes, an atom, as soon as it reaches this state, becomes a true perpetual motion machine, the electrons continuing to move in their orbits (at any rate on Bohr's theory) without any of the energy of their motion being dissipated away, either in the form of radiation or otherwise. It seems

astonishing and quite incomprehensible that an atom in such a state should not be able to yield up its energy still further, but, so far as our experience goes, it cannot. And this property, little though we understand it, is, in the last resort, responsible for keeping the universe in being. If no restriction of this kind intervened, the whole material energy of the universe would disappear in the form of radiation in a few thousand-millionth parts of a second. If the normal hydrogen atom were capable of emitting radiation in the way demanded by the nineteenth-century laws of physics, it would, as a direct consequence of this emission of radiation, begin to shrink at the rate of over a metre a second, the electron continually falling to orbits of lower and lower energy. After about a thousand-millionth part of a second the nucleus and the electron would run into one another, and the whole atom would probably disappear in a flash of radiation. By prohibiting any emission of radiation except by complete quanta, and by prohibiting any emission at all when there are no quanta available for dissipation, the quantum theory succeeds in keeping the universe in existence as a going concern.

It is difficult to form even the remotest conception of the realities underlying all these phenomena. The recent branch of physics known as "wave-mechanics" is at present groping after an understanding, but so far progress has been in the direction of co-ordinating observed phenomena rather than in getting down to realities. Indeed, it may be doubted whether we shall ever properly understand the realities ultimately involved; they may well be so fundamental as to be beyond the grasp of the human mind.

It is just for this reason that modern theoretical physics is so difficult to explain, and so difficult to understand. It is easy to explain the motion of the

earth round the sun in the solar system. We see the sun in the sky; we feel the earth under our feet, and the concept of motion is familiar to us from everyday experience. How different when we try to explain the analogous motion of the electron round the proton in the hydrogen atom! Neither you nor I have any direct experience of either electrons or protons, and no one has so far any inkling of what they are really like. So we agree to make a sort of model in which the electron and proton are represented by the simplest things known to us, tiny hard spheres. The model works well for a time and then suddenly breaks in our hands. In the new light of the wave-mechanics, the hard sphere is seen to be hopelessly inadequate to represent the electron. A hard sphere has always a definite position in space; the electron apparently has not. A hard sphere takes up a very definite amount of room, an electron—well, it is probably as meaningless to discuss how much room an electron takes up as it is to discuss how much room a fear, an anxiety or an uncertainty takes up, but if we are pressed to say how much room an electron takes up, perhaps the best answer is that it takes up the whole of space. A hard sphere moves from one point to the next; our model electron, jumping from orbit to orbit in Bohr's model hydrogen atom, certainly does not behave like any hard sphere of our waking experience, and the real electron —if there is any such thing as a real electron—probably even less. Yet as our minds have so far failed to conceive any better picture of the atom than this very imperfect model, we can only proceed by describing phenomena in terms of it.

THE MECHANICAL EFFECTS OF RADIATION

The more compact an electrical structure is, the greater the amount of energy necessary to disturb it; and, as this energy must be supplied in the form of a single quantum, the greater the energy of the quantum must be, and so the shorter the wave-length of the radiation. A very compact structure can only be disturbed by radiation of very short wave-length.

A ship heading into a rough sea runs most risk of damage, and its passengers most risk of discomfort, when its length is about equal to the length of the waves. Short waves disturb a short ship and long waves a long ship, but a long swell does little harm to either. But this provides no real analogy with the effects of radiation, since the wave-length of radiation which breaks up an electrical structure is hundreds of times the size of the structure. The nautical analogy to such radiation is a very long swell indeed. As a rough working guide we may say that an electrical structure will only be disturbed by radiation whose wave-length is about equal to 860 times the dimensions of the structure, and will only be broken up by radiation whose wave-length is below this limit*. In brief, the reason why blue light affects photographic plates, while red light does not, is that the wave-length of blue light is less, and that of red light is greater, than 860 times the

* The mathematician will readily see the reason for this rule, which is, in brief, as follows: the energy needed to separate two electric charges $+e$ and $-e$, at a distance r apart, is e^2/r, and the energy needed to re-arrange or break up a structure of electrons and protons of linear dimensions r will generally be comparable with this. If λ is the wave-length of the requisite radiation, the energy made available by the absorption of this radiation is the quantum hC/λ. Combining this with the circumstance that the value of h is very approximately $860\ e^2/C$, we find that the requisite wave-length of radiation is about 860 times the dimensions of the structure to be broken up.

diameter of the molecule of silver bromide; we must get below the "860-limit" before anything begins to happen.

When an atom discharges its reservoir of stored energy, the light it emits has necessarily the same wave-length as the light which it absorbed in originally storing up this energy; the two quanta of energy being equal, their wave-lengths are the same. It follows that the light emitted by any electrical structure will also have a wave-length of about 860 times the dimensions of the structure. Ordinary visible light is emitted mainly by atoms, and so has a wave-length equal to about 860 atomic diameters. Indeed, it is just because it has this wave-length that the light acts on the atoms of our retina, and so is visible.

Radiation of this wave-length disturbs only the outermost electrons in an atom, but radiation of much shorter wave-length may have much more devastating effects; X-radiation, for instance, may break up the far more compact inner rings of electrons, the *K*-ring, *L*-ring, etc., of the atomic structure. Radiation of still shorter wave-length may even disturb the protons and electrons of the nucleus. For the nuclei, like the atoms themselves, are structures of positive and negative electrical charges, and so must behave similarly with respect to the radiation falling upon them, except for the wide difference in the wave-length of the radiation. Ellis and others have found that the γ-radiation emitted during the disintegration of the atoms of the radioactive element radium B has wave-lengths of 3·52, 4·20, 4·80, 5·13, and 23×10^{-10} cm. These wave-lengths are only about a hundred-thousandth part of those of visible light, the reason being that the atomic nucleus has only about a hundred-thousandth part the dimensions of the complete atom. Radiation of such wave-lengths ought to be just as effective in re-arranging the

nucleus of radium-B as that of 100,000 times longer wave-length is effective in re-arranging the hydrogen atom.

Since the wave-length of the radiation absorbed or emitted by an atom is inversely proportional to the quantum of energy, the quantum needed to "work" the atomic nucleus must have something like 100,000 times the energy of that needed to "work" the atom. If the hydrogen atom is a penny-in-the-slot machine, nothing less than five-hundred-pound notes will work the nuclei of the radio-active atoms.

The radio-active nuclei, like those of nitrogen and oxygen, could probably be broken up by a sufficiently intense bombardment, although the experimental evidence on this point is not very convincing. If so, each bombarding particle would have to bring to the attack an energy of motion equal at least to that of one quantum of the radiation in question, this requiring it to move with an enormously high speed. Matter at sufficiently high temperatures contains an abundant supply both of quanta of high energy, and of particles moving with high speeds.

TEMPERATURE-RADIATION. We speak in ordinary life of a red-heat or a white-heat, meaning the heat to which a substance must be raised to emit red or white light respectively. The filament in a carbon-filament lamp is said to be raised to a red-heat, that in a gas-filled lamp to a yellow-heat. It is not necessary to specify the substance we are dealing with; if carbon emits a red light at a temperature of 3000°, then tungsten or any other substance, raised to this same temperature, will emit exactly the same red light as the carbon, and the same is true for other colours of radiation. Thus each colour, and so also each wave-length of radiation, has a definite temperature associated with it, this being the temperature at which this particular colour is most

abundant in the spectroscopic analysis of the light emitted by a hot body. As soon as this particular temperature begins to be approached, but not before, radiation of the wave-length in question becomes plentiful; at temperatures well below this it is quite inappreciable*.

Just as we speak of a red-heat or a white-heat, we might, although we do not do so, quite legitimately speak of an X-ray heat or a γ-ray heat. The shorter the wave-length of the radiation, the higher the temperature specially associated with it. Thus, as we make a substance hotter and hotter, it emits light of ever shorter wave-length, and runs in succession through the whole rainbow of colours—red, orange, yellow, green, blue, indigo, violet. We cannot command a sufficient range of temperature to perform the complete experiment in the laboratory, but nature performs it for us in the stars.

THE EFFECTS OF HEAT. We have already seen that radiation of short wave-length is needed to break up an electric structure of small dimensions. As short wave-lengths are associated with high temperatures, it now appears that the smaller an electrical structure is, the greater the heat needed to break it up. And we can calculate the temperature at which an electric structure of given dimensions will first begin to break up under the influence of heat†.

For instance, an ordinary atom with a diameter of about 4×10^{-8} cm. will first be broken up at tempera-

* The wave-length λ of the radiation and the associated temperature T (measured in Centigrade degrees absolute) are connected through the well-known relation:

$$\lambda T = 0{\cdot}2885 \text{ cm. degree.}$$

† On combining the relation just given between T and λ with that implied in the rough law of the "860-limit," we find that a structure whose dimensions are r cms. will begin to be broken up by temperature-radiation when the temperature first approaches $1/3000r$ degrees.

tures of the order of thousands of degrees. To take a definite example, yellow light of wave-length 0·00006 cm. is specially associated with the temperature 4800 degrees; this temperature represents an average "yellow-heat." At temperatures well below this, yellow light only occurs when it is artificially created. But stars, and all other bodies, at a temperature of 4800 degrees emit yellow light naturally, and show lines in the yellow region of their spectrum, because yellow light removes the outermost electron from the atoms of calcium and similar elements. The electrons in the calcium atom begin to be disturbed when a temperature of 4800 degrees begins to be approached, but not before. This temperature is not approached on earth (except in the electric arc and other artificial conditions), so that terrestrial calcium atoms are generally at rest in their states of lowest energy.

To take another instance, we have seen that the shortest wave-length of the γ-radiation emitted during the disintegration of radium B is $3{\cdot}52 \times 10^{-10}$ cm.; this corresponds to a temperature of 820,000,000 degrees. The shortest wave-length for uranium is $0{\cdot}5 \times 10^{-10}$ cm., which corresponds to the enormously high temperature of 5,800,000,000 degrees. When such terrific temperatures as these begin to be approached, but not before, the constituents of the radio-active nuclei ought to begin to re-arrange themselves, just as the constituents of the calcium atom do when a temperature of 4800 degrees is approached. And if we suppose that re-arrangements of an electric structure can also be effected by bombarding it with material particles, the temperature at which bombardment by electrons, nuclei, or molecules first becomes effective is about the same as that at which radiation of the effective wave-length would first begin to be appreciable; the two processes begin at approximately

the same temperature. This of course explains why no temperature we can command on earth has any appreciable effect in expediting or inhibiting radio-active disintegration.

The table on p. 160 shews the wave-lengths of the radiation necessary to effect various atomic transformations. The last two columns shew the corresponding temperatures, and the kind of place, so far as we know, where this temperature is to be found, these latter entries anticipating certain results which will be given in detail in Chapter v below (p. 305 ff.). In places where the temperature is far below that mentioned in the last column but one, the transformation in question cannot be effected by heat, and so can only occur spontaneously. Thus it is entirely a one-way process. The available radiation not being of sufficiently short wave-length to work the atomic slot-machine, the atoms absorb no energy from the surrounding radiation and so are continually slipping back into states of lower energy, if such exist.

The shortest wave-lengths we have so far had under discussion are those of the γ-rays, but the last line of the table refers to the possible existence of radiation having a wave-length of less than a thousandth part of that of the shortest of γ-rays. This we must now discuss.

HIGHLY PENETRATING RADIATION

When the molecules of a gas are shattered by the incidence of radiation in the way we have already explained, the gas is said to be "ionised" and becomes a good conductor of electricity. In and after 1902 Rutherford, McLennan and others found evidence of extensive ionisation in the air surrounding their instruments, and suspected that this might arise from γ-radiation, possibly produced by radio-active sub-

The Mechanical Effects of Radiation

Wave-lengths (cm.)	Nature of Radiation	Effect on Atom	Temperature (degrees abs.)	Where found
7500×10^{-8} to 8750×10^{-8}	Visible light	Disturbs outermost electrons	8,850° to 7,700°	Stellar atmospheres
250×10^{-8} to 10^{-8}	X-rays	Disturbs inner electrons	115,000° to 29,000,000°	Stellar interiors
5×10^{-9} to 10^{-9}	Soft γ-rays	Strips off all or nearly all electrons	58,000,000° to 290,000,000°	Central regions of dense stars
4×10^{-10}	γ-rays of radium B	Disturbs nuclear arrangement	720,000,000°	?
5×10^{-11}	Shortest γ-rays	—	5,800,000,000°	?
$1{\cdot}3 \times 10^{-13}$	Highly penetrating γ-radiation (?)	Annihilation or creation of proton and accompanying electron	2,200,000,000,000°	Cosmic radiation?
$0{\cdot}82 \times 10^{-13}$	do. (hardest component)	Annihilation or creation of α-particle and two accompanying electrons	8,800,000,000°	Cosmic radiation?

stances in the earth's crust. However, by sending up balloons to great heights, Hess, Kolhörster, and later Millikan and Bowen, have shewn that the radiation is noticeably more intense at great heights, from which they conclude that it comes into the earth's atmosphere from outside. If the radiation had its origin in the sun and stars, the main part of the radiation received on earth would come from the sun, so that the radiation would be more intense by day than by night. This is found not to be the case, so that the radiation cannot come from the sun and stars. For this reason it is generally supposed to originate in nebulae or cosmic masses other than stars, and is frequently described as "Cosmic radiation."

The amount of this radiation is very great. Even at sea-level, where it is least, Millikan and Cameron find that it breaks up about ten atoms in every cubic inch of air each second. It must break up millions of atoms in each of our bodies every second—and we do not know what its physiological effects may be. Regener has recently (1933) estimated that the total energy of the radiation received on earth is very nearly equal to that of the total radiation, light and heat together, received from all the stars. This does not mean that light and heat are as abundant as this radiation in the universe as a whole. For if the radiation originates in extra-galactic regions, then the stars which send us light and heat are comparatively near, while the sources of the highly penetrating radiation are far more remote. On taking an average through the whole of space, including the vast stretches of internebular space, it seems likely that the highly penetrating radiation is enormously more plentiful than stellar light and heat, and so is the most abundant form of radiation in the whole universe.

It is the most penetrating form of radiation known.

Ordinary light will hardly pass through metals or solid substances at all; only a tiny fraction emerges through the thinnest of gold-leaf. On account of their shorter wave-length, and so of their more energetic quanta, X-rays will pass through foils of a few millimetres thickness of gold or of lead. The most highly penetrating γ-rays from radium B will pass through inches of lead. The radiation we have just been discussing varies in penetrating power; the most penetrating part of it will pass through many yards of lead.

It is not altogether clear whether the radiation is of the nature of very short γ-radiation or is of a corpuscular nature, like β-radiation; it may even be a mixture of both. Its penetrating power far exceeds that of any known β-radiation, and calculation shews that if it is corpuscular, the corpuscles must be moving with very nearly the velocity of light.

Because of its immense powers of penetration, this radiation must pass through the sparse matter of interstellar space so freely that, when once it has been set free in space, it may fairly be regarded as indestructible. For, as we have already seen, the amount of matter in space, including the masses of the stars and nebulae, is probably only sufficient to give an average density in space of the order of 10^{-30} gramme to the cubic centimetre. This means that radiation must travel over an average path of 10^{30} centimetres before encountering as much matter as there is in a layer of water one centimetre in thickness. Radiation travelling with the speed of light requires a million million years to traverse this length of path; corpuscles or charged particles must necessarily travel more slowly than light, and so would take an even longer time. In this length of time the decrease in the radiation is only that due to traversing a single centimetre of water, and so is quite inappreciable; the radiation must travel for hundreds of

millions of millions of years before experiencing any appreciable diminution in strength. In view of what we shall find later as to the probable age of the universe this means that the radiation is virtually inextinguishable; practically all that has ever been generated since time began is still wandering round and round space. The question of primary interest, however, is not when or where the radiation was generated, but how.

It might seem easy to test whether the radiation is a kind of γ-radiation, or consists of particles or corpuscles, by observing whether or not the radiation is bent in a magnetic field, but actually the problem is one of very great complexity. The one certain and outstanding property of the radiation is its capacity to shatter molecules on which it falls. The *débris* of these molecules then follows the original radiation on its course, so that by the time the radiation reaches the earth, it is in any event likely to consist of a mixture of particles of various kinds and of waves of varied wavelengths, as is in fact found to be the case. Unhappily it is impossible to pass beyond the earth's atmosphere and study the original radiation before it is complicated by the admixture of its own by-products.

If the original radiation consists of particles, charged either positively or negatively, these must move with prodigious speeds, approximating very nearly to the velocity of light. Any lower speed would be incompatible with the enormous penetrating power of the radiation. As a shower of such rapidly moving particles approached the earth's surface, it would be greatly influenced by the magnetic field of the earth. Various investigators have made careful studies of the effects to be expected. They find that electrons moving with less than a certain critical speed can only reach the earth in certain small circles surrounding the two magnetic poles of the earth; all other parts of the earth's

surface are sheltered by the magnetic forces which the earth's magnetism exerts on moving electrified particles. On the other hand, there is no such limitation for particles moving with far higher speeds; these would fall uniformly all over the surface of the earth. To this extent, then, they would behave in the same way as γ-radiation which also of course is unaffected by the earth's magnetic field.

For a long time it was believed that the cosmic radiation fell uniformly over all parts of the earth's surface, in which case the original radiation might have been either γ-radiation or very swiftly moving charged particles. Recently, however, a series of expeditions organised by A. H. Compton and two other American professors to study the geographical distribution of the cosmic rays, have found that this varies quite distinctly with the latitude; at sea-level there is a difference of about 14 per cent. between equator and poles, and this difference increases with altitude above the earth's surface—just in the way it would if the original radiation consisted of charged particles.

This makes it highly probable that a large part of the original cosmic radiation must consist of charged particles—whether electrons, protons, α-particles or positrons, it is impossible to say. It is more difficult to decide whether a further part of the radiation is of the nature of γ-radiation; Professor Compton thinks not.

On the other hand, a great number of experimenters have found that the radiation consists of a mixture of constituents of very different penetrating powers. The reality of these constituents is vouched for by the circumstance that, broadly speaking, different investigators agree fairly well in the penetrating powers they assign to them. The most recent measurements of Regener shew the existence of constituents which lose

only 1 per cent. of their intensity in passing through 50 cms. and 14 cms. of water respectively, while Kolhörster has discovered an even more penetrating constituent which loses less than 1 per cent. of its intensity in passing through two metres of water.

If we tentatively identify these various constituents with γ-radiations of different wave-lengths, we can calculate the wave-lengths from the observed penetrating powers. The two shortest wave-lengths are those inserted in the table on p. 160, namely $1{\cdot}3 \times 10^{-13}$ cm. and $0{\cdot}32 \times 10^{-13}$ cm.

We perhaps get the clearest conception of what these wave-lengths mean if we apply the 860-rule; this shews that the radiation of wave-length $1{\cdot}3 \times 10^{-13}$ cm. would break up an electric structure whose dimensions are only about 10^{-16} cm. No structure formed of electrons and protons can possibly be as small as this, for the radius of a single electron is about 2×10^{-13} cm. The radiation is of about the wave-length needed to break up the proton itself, the smallest and most compact structure known to science.

Approaching the problem from another angle, the numerical relations already given shew that a quantum of radiation of this wave-length must have energy equal to 0·0015 erg, and so must have a weight of about $1{\cdot}66 \times 10^{-24}$ gramme. Every physicist recognises this weight at once, for the best determinations give the weight of the hydrogen atom as $1{\cdot}662 \times 10^{-24}$ gramme. The quantum of highly penetrating radiation has, then, just about the weight, and just about the energy, that would result from a complete hydrogen atom suddenly being annihilated and having all its energy set free as radiation—or of course from the simultaneous annihilation of any proton and a neutralising electron. A similar calculation shews that the shorter wave-length of $0{\cdot}32 \times 10^{-13}$ cm. is just about

that which would result from the annihilation of a complete helium atom or, again, of an α-particle and two neutralising electrons.

We may reverse our procedure, imagine these processes of annihilation to take place, and calculate the wave-length and hence the penetrating power of the ensuing radiation. The result is shewn in the following table, in which the second column gives the theoretically calculated absorption per metre of water (as a percentage of total intensity) while the last column gives the absorption, as observed by Regener, for the two most penetrating constituents of the actual cosmic radiation:

Process	Absorption per metre as percentage of whole	
	Calculated	Observed
Annihilation of proton and electron	0·071	0·073
Annihilation of α-particle and two electrons	0·0204	0·0205

The agreement appears rather too good to be true, but is probably also too good to be dismissed as purely accidental, and seems rather to suggest that the most penetrating constituents of all may be of the nature of γ-radiation, although having wave-lengths far shorter than any γ-radiation hitherto known. If this is the true interpretation, then the cosmic radiation brings with it evidence of the annihilation of matter in outer space—occurring either recently or countless ages ago (p. 163).

We have already seen (p. 135) that recent atomic physics provides evidence that matter may not be the ever-enduring, uncreatable and indestructible affair we

once thought it. It may be that the cosmic radiation will in time be found to provide further evidence to the same effect, although it must be freely admitted that the whole question is in so uncertain a state that it would be mere folly to claim to draw any conclusions at present.

CHAPTER III

Exploring in Time

We have explored space to the farthest depths to which our telescopes can probe; we have explored into the intricacies of the minute structures we call atoms, of which the whole material universe is built; we now wish to go exploring in time. Man's individual span of life, and indeed the whole span of time covered by our historical records—some few thousands of years at most—are both far too short to be of any service for our purpose. We must find far longer measuring-rods with which to sound the depths of past time and to probe forward into the future.

Our general method will be one which the study of geology has already made familiar. Undeterred by the absence of direct historical evidence, the geologist insists that life has existed on earth for millions of years, because fossil remains of life are found to occur under deposits which, he estimates, must have taken millions of years to accumulate. As he digs down through different strata in succession, he is exploring in time just as truly as the geographer who travels over the surface of the earth is exploring in space. A similar method can be used by the astronomer. We find some astronomical effect, quality, or property, which exhibits a continual accumulation or decrease, like the sand in the bottom or top half of the hour-glass; we estimate the rate at which this increase or decrease is occurring at the present moment, and also, if we can, the rate at which it must have occurred under the different conditions prevailing in the past. It then becomes a question, perhaps of mere arithmetic, although possibly of more complicated mathe-

matics, to estimate the time which has elapsed since the process first started.

THE AGE OF THE EARTH

The method is well exemplified in the comparatively simple problem of the age of the earth.

The first scientific attempt to fix the age of the earth was made by Halley, the astronomer, in the year 1715. Each day the rivers carry a certain amount of water down to the sea, and this contains small amounts of salt in solution. The water evaporates and in due course returns to the rivers; the salt does not. As a consequence the amount of salt in the oceans goes on increasing; each day they contain a little more salt than they did on the preceding day, and the present salinity of the oceans gives an indication of the length of time during which the salt has been accumulating. "We are thus furnished with an argument," said Halley, somewhat optimistically, "for estimating the duration of all things."

This line of argument does not lead to very precise estimates of the earth's age, but calculations based on modern data suggest that it must be many hundreds of millions of years.

More valuable information can be obtained from the accumulation of sediment washed down by the rain. Every year that passes witnesses a levelling of the earth's surface. Soil which was high up on the slopes of hills and mountains last year has by now been washed down to the bottoms of muddy rivers by the rain and is continually being carried out to sea. The Thames alone carries between one and two million tons of soil out to sea every year. For how long will England last at this rate, and for how long can it have already lasted? In our own lifetimes we have seen large masses of land

round our coasts form landslides, and either fall wholly into the sea or slip down nearer to sea-level. Such conspicuous land-marks as the Needles, and indeed a large part of the southern coast of the Isle of Wight, are disappearing before our eyes. The geologist can form an estimate of the rapidity with which these and similar processes are happening, and so can estimate how long sedimentation has been in progress to produce the observed thickness of geological layers.

These thicknesses are very great; Professor Arthur Holmes gives the observed maximum thicknesses as follows:

Cainozoic Era (modern life)	73,000 feet
Mesozoic Era (mediaeval life)	91,000 ,,
Palaeozoic Era (ancient life)	185,000 ,,
Pre-cambrian Eras (still earlier life, primaeval life, and dawn of life)	at least 180,000 ,,
Total—at least	529,000 feet

We can form a general idea of the rate at which these sediments have been deposited. Since Rameses II reigned in Egypt over 3000 years ago, sediment has been deposited at Memphis at the rate of a foot every 400 or 500 years; the excavator must dig down 6 or 7 feet to reach the surface of Egypt as it stood when Rameses II was king. Yet a foot of this material ultimately forms only a few inches of rock; to deposit a single foot of rock is a matter of thousands of years. The present rate of denudation in North America is estimated to be one foot in 8600 years; similar estimates for Great Britain indicate a rate of one foot in 3000 years.

With geological strata deposited at an average rate of one foot per 1000 years, the total 529,000 feet of strata listed above would require over 500 million years for their deposition. At a rate of one foot per 4000 years,

the time would be about 2100 million years. Estimates from the rates of denudation suggest similar figures.

This method of estimating geological time has been described as the "Geological hour-glass." We see how much sand has already run, we notice how fast it is running now, and a calculation tells us how long it is since it first started to run. The method suffers from the usual defect of hour-glasses, that there is no guarantee that the sand has always run at a uniform rate. Geological methods suffice to shew that the earth must be hundreds of millions of years old, but to obtain more definite estimates of its age the more precise methods of physics and astronomy must be called in. Fortunately the radio-active atoms discussed in the previous chapter provide a perfect system of clocks, whose rate, so far as we know, does not vary by a hair's breadth from one age to another.

We have seen how, with the lapse of sufficient time, an ounce of uranium disintegrates into 0·865 ounce of lead and 0·135 ounce of helium. The process of disintegration is absolutely spontaneous; no physical agency known in the whole universe can either inhibit or expedite it in the tiniest degree. The following table shews the rate at which it progresses:

History of One Ounce of Uranium

Initially:	1 oz. uranium	No lead
After 100 million years	0·985 oz. uranium	0·013 oz. lead
,, 1000 ,,	0·865 ,, ,,	0·116 ,, ,,
,, 2000 ,,	0·747 ,, ,,	0·219 ,, ,,
,, 3000 ,,	0·646 ,, ,,	0·306 ,, ,,

and so on. Thus, a small amount of uranium provides a perfect clock, provided we are able to measure the amount of lead it has formed, and also the amount of uranium still surviving, at any time we please. When the earth first solidified, many fragments of uranium were imprisoned in its rocks; these may now be used

to disclose the age of the earth. We are not entitled to assume that all the lead which is found associated with uranium has been formed by radio-active disintegration. But, by a fortunate chance, lead which has been formed by the disintegration of uranium is just a bit different from ordinary lead; the latter has an atomic weight of 207·2, while the former is of atomic weight only 206·0. Thus, a chemical analysis of any sample of radio-active rock shews exactly how much of the lead present is ordinary lead, and how much has been formed by radio-active disintegration. The proportion of the amount of lead of this latter kind to the amount of uranium still surviving tells us exactly for how long the process of disintegration has been going on.

In general all samples of rock which are drawn from the same geological strata tell the same story, and so enable us to fix the age since the deposition of the strata in question. This enables us to construct a time-table, somewhat as follows:

	Duration Millions of years	Total
Cainozoic or modern life (mammals, toothless birds, flowers)	60	60
Mesozoic or mediaeval life (enormous reptiles, toothed birds)	140	200
Palaeozoic or ancient life (fishes in sea, vegetation on land)	400 (?)	600 (?)
Pre-cambrian (primitive life)	400 (?)	1,000 (?)

In this way we can fix the duration of life on earth at something between 300 million and 1000 million years. It is less easy to fix the age of the earth itself. The oldest rocks so far examined shew an age of 1400 million years, so that this is the minimum time which can have elapsed since the earth solidified. But the radio-active clock cannot tell us for how long before this the earth

had existed in a plastic or fluid state, since in this earlier state the products of disintegration were liable to become separated from one another, so that we must look to other sources for this information.

Aston has recently discovered a new isotope (see p. 180) of uranium, called actino-uranium. As uranium and its isotope have different periods of decay, the relative abundance of the two is continually changing. From the ratio of the amounts of these substances now surviving on earth, Rutherford has calculated that the age of the earth cannot exceed 3400 million years, and is probably substantially less.

Again, it is estimated that a million grammes of average igneous rock contain 7·5 grammes of lead, 6 grammes of uranium, and 15 grammes of thorium. From this, Professor H. N. Russell has calculated that even if all the lead were of radio-active origin, the age of the earth could not be greater than 3000 million years. Actually it must be less—partly because some of the lead in question may not be of radio-active origin at all, partly because some even of the radio-active lead may have been produced in the sun before the earth became detached from it (see p. 256 below).

These two physical estimates of the time which has elapsed since the earth solidified stand as follows:

Age of the Earth by the Radio-active Clock

1. From the lead-uranium ratio in radio-active rocks	More than 1400 million years.
2. From the relative abundance of uranium and actino-uranium	Less than 3400 million years.
3. From the lead content of igneous rocks	Less than 3000 years.

Various astronomical methods are also available for determining the time since the solar system came into

being. Here "clocks" are provided by the shapes of the orbits of various planets and satellites. The orbits do not change at uniform rates, but their changes are determined by known laws, so that the mathematician can calculate the rates at which change occurred under past conditions, and hence, by totalling up, can deduce the time needed to establish present conditions. The following two estimates are both due to Dr H. Jeffreys:

Age of the Solar System by the Astronomical Clock

1. From the orbit of Mercury	...	From 1000 to 10,000 million years.
2. ,, ,, the Moon	...	Roughly about 4000 million years.

A further clock is provided by the radio-activity of meteoric stones (p. 268). These give estimates ranging from a few hundred million years up to 2900 million years.

While these various figures do not lead to any very exact estimate of the earth's age, they all indicate that this must be measured in thousands of millions of years. If we wish to fix our thoughts on a round number, probably 2000 million years is the best to select.

THE AGES OF THE STARS

We now turn to the far more difficult problem of determining the ages of the stars.

We shall not approach it by a direct frontal attack, but shall start far away from our real objective. Let us in fact start at the extreme other end of the universe, and delve a bit farther than we have hitherto done into the properties of a gas.

EQUIPARTITION OF ENERGY IN A GAS. We have pictured a gas as an indiscriminate flight of molecule-bullets. These fly equally in all directions, occasionally crashing into one another, and in so doing, changing both their speeds and directions of flight. We have seen

that the total energy of motion undergoes no decrease when such collisions occur. If one of the molecules taking part in a collision has its speed checked, the other has its speed increased by such an amount that the energy lost by one molecule is gained by the other. Total energy of motion is "conserved."

Into this random hail of bullets, let us imagine that we project a far heavier projectile, which we may call a cannon-ball, with a speed equal to about the average speed of the bullets. We have seen (p. 113) that the energies of the various projectiles are proportional jointly to their weights and to the squares of their speeds, so that in the present case, in which the speeds are all much the same, the big projectile has more energy than the bullets simply on account of its greater weight. If it weighs as much as a thousand bullets, it has a thousand times as much energy as each single bullet.

Yet the heavy projectile cannot for long continue swaggering through its lesser companions with a thousand times its fair share of energy. Its first experience is to encounter a hail of bullets on its chest. Very few bullets hit it in the back, for they are only moving at about its own speed, and so can hardly overtake it from behind. Moreover, even if they do, their blows on its back are very feeble because they are hardly moving faster than it. But the shower of blows on its chest is serious; every one of these tends to check its speed, and so to lessen its energy. And as the total energy of motion is conserved at every collision, it follows that, while the big projectile is losing energy all the time, the little ones must be gaining energy at its expense.

For how long will this interchange of energy go on? Will it, for instance, continue until the big projectile has lost all its energy, and been brought completely

to rest? The problem is one for the mathematician, and it admits of a perfectly exact mathematical solution, which Maxwell gave as far back as 1859. The big projectile is not deprived of all its energy. As its speed gradually decreases, conditions change in all sorts of ways. When we allow for this change of conditions, we find that the energy of the big projectile goes on decreasing, not until it has lost all its energy, but until it has no more energy than the average bullet. When this stage is reached, the hits of the bullets are as likely on the average to increase the energy of the big projectile as to decrease it, so that this ends up by fluctuating around an amount equal to the average energy of the little projectiles.

Maxwell, and others after him, further shewed that no matter how many kinds of molecules there may be mixed together in a gas, and no matter how widely their weights may differ from one another, their repeated collisions must ultimately establish a state of things in which big molecules and little, light and heavy, all have the same average energy. This is known as the theorem of equipartition of energy. It does not mean that at any single instant all the molecules have precisely the same energy; obviously such a state of things could not continue for a moment, since the first collision between any pair of molecules would upset it immediately. But on averaging the energy of each molecule over a sufficiently long period of time—say a second, which is a very long time indeed in the life of a molecule, being the time in which at least a hundred million collisions occur—we shall find that the average energy of all the molecules is the same, regardless of their weights.

The same theorem can be stated in a slightly different form. Air consists of a mixture of molecules of different kinds and of different weights—molecules

of helium which are very light, molecules of nitrogen which are far heavier, each weighing as much as seven molecules of helium, and the still heavier molecules of oxygen, each with the weight of eight molecules of helium. In its alternative form, the theorem tells us that at any instant the average energy of all the molecules of helium, in spite of their light weights, is exactly equal to the average energy of the molecules of nitrogen, and again each of these is exactly equal to the average energy of the molecules of oxygen. The lighter types of molecule make up for their small weights by their high speeds of motion. Similar statements are of course true for any other mixture of gases.

The truth of the theorem is confirmed observationally in a great variety of ways. In 1846 Graham measured the relative speeds with which the molecules of different kinds of gas moved, by observing the rates at which they streamed through an orifice into a vacuum; these proved to be such that the average energies of the various types of molecules were precisely equal to one another. Even earlier than this Leslie and others had used this method to determine the relative weights of different molecules, although without fully understanding the underlying theory. Thus, it may be accepted as a well-established law of nature that no molecule is allowed permanently to retain more energy than his fellows; in respect of their energies of motion, a gas forms a perfectly organised communistic state in which a law, which they cannot evade, compels the molecules to share their energies equally and fairly.

Subject to certain slight modifications, the same law applies also to liquids and solids.

In liquids and gases, it is possible to perform an experiment analogous to that of projecting our imaginary

cannon-ball into the hail of molecule-bullets, and watch events. We may take a few grains of very fine powder, such as powdered gamboge or lycopodium seed, and let these play the part of super-molecules amongst the ordinary molecules of a gas or liquid. A powerful microscope shews that these super-molecules are not brought completely to rest, but retain a certain liveliness of movement, as they are repeatedly hit about by the smaller and quite invisible true molecules. It looks for all the world as though they were affected by a chronic St Vitus' dance, which shews no signs of diminishing as time goes on. These movements are called "Brownian movements," after Robert Brown, the botanist, who first observed them in the sap of plants. Brown at first interpreted them as evidence of real life in the small particles affected by them, an interpretation which he had to abandon when he found that particles of wax shewed the same movements. In a series of experiments of amazing delicacy, Perrin not only observed, but also measured, the Brownian movements of small solid particles as they were hit about by the molecules of air and other gases, and deduced the weights of the molecules of these gases with great accuracy.

STELLAR EQUIPARTITION OF ENERGY. We can now get back to the stars. The theorem of equipartition of energy is true not only of the molecules of a gas, and of a solid, and of a liquid; it is true also of the stars of the sky. The processes of mathematics are applicable to the very great as well as to the very small, and a theorem which is proved true for the minutest of atoms is equally true for the most stupendous of stars, provided of course that the premisses on which it is based remain true, and do not suffer by transference from the small to the great end of the universe.

Now the conditions which are necessary for the

theorem of equipartition of energy to be true happen to be amazingly simple; indeed, it is difficult to believe that such wide consequences can follow from such simple conditions. They amount to practically nothing beyond a law of continuity and a law of causation; in other words, that the state of the system at any instant shall follow inevitably from its state at the preceding instant, or, if you like, that there shall be no free-will among the molecules or stars or other bodies whose motions are under discussion. In the present turmoil as to the fundamental laws of physics, we cannot be entirely certain as to how far these very simple conditions are fulfilled in the molecular problem, although abundant observational evidence makes it clear that the law of equipartition holds, at any rate to an exceedingly good approximation, in an ordinary gas.

On the other hand, there is not the slightest doubt as to what determines the motions of the stars; it is the law of gravitation, every star attracting every other star with a force which varies inversely as the square of their distance apart. This is Newton's form of the law, but it is a matter of complete indifference for our present purpose whether we use the law in Newton's or in Einstein's form; for stellar problems the two are practically indistinguishable, and there is abundant evidence, particularly from the observed orbits of binary stars, in favour of either. The essential point is that, from the single supposition that the motions of the stars are governed by either of these laws of gravitation—or, for the matter of that, by any other not entirely dissimilar law—we can prove the theorem of equipartition of energy to be true for these motions. No subtle statement of exact conditions is required; the mere law of gravitation, together with the supposition that the stars cannot exercise free-will as to whether they obey it or not, is enough.

It is important to understand quite clearly what precisely the theorem asserts when applied to the stars. It does not of course assert that all the stars in the sky have equal energies. It does not even assert that on the average the heavy-weight stars in the sky have the same energy as the light-weight stars. What it asserts is that if we put any miscellaneous assortment of stars into space, then, after they have interacted with one another *for a sufficient length of time* (this is the essential point), those which started with more than their fair share of energy will have been compelled to hand over their excess to stars with lesser energy, so that the average energy of all the different types of stars must necessarily become reduced to equality *in the long run.*

In the molecular problem, the interaction between the molecules takes place through the medium of collisions, and equipartition of energy is established, to a very good approximation, after some eight or ten collisions have happened to each molecule. In ordinary air, this requires a period of only about a hundred-millionth part of a second.

In the stellar problem, we are dealing with very different lengths of time; collisions only occur at intervals of thousands of millions of millions of years. If the stars only redistributed their energy when actual collisions occurred, we might surmise that a close approximation to equipartition of energy would not be attained until after each star had experienced eight or ten collisions, and this would require a really stupendous length of time. Actually no such length of time is needed because the numerous gravitational pulls, even between stars which are at a considerable distance apart, equalise energy far more efficiently and expeditiously than the very rare direct hits. Every time that two stars happen to pass even fairly near to one

another in their wanderings, each pulls the other a bit out of its course, and the directions and speeds of motion of both stars are changed—by much or little according as the stars pass quite close to one another or keep at a substantial distance apart. In brief, each approach of stars causes an interchange of energy, and after sufficient time, these repeated interchanges of energy result in the total energy being shared equally, on the average, between the stars, regardless of differences in their weights.

Now the crux of the situation, to which all this has been leading up, is that observation shews that stars of different weights are moving with different average speeds, these average speeds being such that equipartition of energy already prevails among the stars—not absolutely exactly, but to a tolerably good approximation.

The question of how long the stars must have interacted to reach such a condition now becomes one of absolutely fundamental importance, for *the answer ought to tell us the ages of the stars.*

STELLAR VELOCITIES. We have already seen (p. 50) how stars which form binary systems can be weighed, such weighings disclosing weights ranging from about a hundred times the weight of the sun to only a fifth of its weight. The speeds of motion of binary systems can be measured in precisely the same way as the speeds of single stars. As far back as 1911 Halm, with an accumulation of such measurements before him, pointed out that the heaviest stars moved the most slowly. He found that, on the average, the heaviest of known stars had approximately the same energy of motion as the lightest, the high speeds of the latter just about making up for the smallness of their weights, and so suggested that the velocities of the stars, like those of the molecules of a gas, might be found to

conform to the law of equipartition of energy. It appeared to be a case of Brownian movements on a stupendous scale.

Since then a great deal more observational evidence has accumulated, and an exhaustive investigation which Dr Seares of Mount Wilson carried out in 1922 leaves very little room for doubt that the motions of the stars shew a real, and fairly close, approximation to equipartition of energy. The table below shews the final result of Seares' discussion.

The stars are first classified according to the different types of spectrum (p. 55) that their light shews when analysed in a spectroscope.

Equipartition of Energy in Stellar Motions

Type of star	Average weight M (grammes)	Average speed C (cms. a sec.)	Average energy $\frac{1}{2}MC^2$ (ergs)	Corresponding temperature (degrees)
Spectral type $B3$	$19{\cdot}8 \times 10^{33}$	$14{\cdot}8 \times 10^{5}$	$1{\cdot}95 \times 10^{46}$	$1{\cdot}0 \times 10^{62}$
,, $B8{\cdot}5$	12·9	15·8	1·62	0·8
,, $A0$	12·1	24·5	3·63	1·8
,, $A2$	10·0	27·2	3·72	1·8
,, $A5$	8·0	29·9	3·55	1·7
,, $F0$	5·0	35·9	3·24	1·6
,, $F5$	3·1	47·9	3·55	1·7
,, $G0$	2·0	64·6	4·07	2·0
,, $G5$	1·5	77·6	4·57	2·2
,, $K0$	1·4	79·4	4·27	2·1
,, $K5$	1·2	74·1	3·39	1·7
,, $M0$	1·2	77·6	3·55	1·7

These different types of stars have very different average weights; the second column of the table shews that they exhibit a range of over 16 to 1. The third column, which gives the average speeds of these different types of stars, shews that the heaviest stars move the most slowly, and the lightest on the whole the most rapidly. The next column gives the average

energy of motion of the different types of stars. This shews that the variation in speeds is just about that needed to make the average energies of all types of stars equal. An exception certainly occurs in the first two lines, which refer to the heaviest stars of all. Apart from these, the remaining ten lines shew a ratio of 10 to 1 in weight, whereas the average deviation of energy from the mean is only one of 9 per cent.

From this we see that the motions of the stars shew a real approach, and even a fairly close approach, to equipartition of energy. The question which naturally presents itself is whether this approximate equality of energy can be attributed to any other cause than long-continued gravitational interaction between the stars. Given sufficient time, this latter agency could undoubtedly produce it, but could anything else produce a similar result? And—most important question of all—could anything else produce the same result in a shorter time?

The last column of the table provides the answer. It shews the temperatures to which a gas would have to be raised, in order that each of its molecules should have the same energy as the different types of stars. This may well seem an absurd calculation. A star weighing millions of millions of millions of tons goes hurtling through space at a speed of about 1,000,000 miles an hour; are we seriously setting out to inquire how hot a gas must be for every single one of its tiny molecules to have the same energy of motion, the same power of doing damage—for that is what energy of motion really amounts to—as the star? The calculation is undoubtedly absurd, and it is meant to be, because it is leading up to a *reductio ad absurdum*. If the observed equipartition of energy were brought about by any physical agency, such as pressure of radiation, bombardment by molecules, by atoms or by high speed

electrons, this agency would have to be at a temperature, or in equilibrium with matter at a temperature, of the order of those given in the last column. These are temperatures of the order of 10^{62} degrees. We can be pretty sure no such temperature exists in nature, whence the argument runs that the observed equipartition of energy cannot have been brought about by physical means, and so must be the result of gravitational interaction between the stars.

The age of the stars is, then, simply the length of time needed for gravitational forces to bring about as good an approximation to equipartition of energy as is observed.

The calculation of this length of time presents a complicated but by no means intractable problem. All the necessary data are available, and as the method of calculation is well understood from previous experience in the theory of gases, the mathematician may be trusted to supply a reliable and reasonably exact answer when we ask him, but even without his help we can see that the time must be very long indeed.

Leaving actual figures aside for the moment, we may find it easier to think in terms of the scale-model we constructed in the first chapter (p. 103). We took our scale so small that the stars were reduced to tiny specks of dust; we noticed that space is so little crowded with stars that in our model the specks of dust had to be placed over 200 yards apart; to put it all in a concrete form, we found that Waterloo Station with only six specks of dust left in it is more crowded with dust than space is with stars. Now let the model come to life, so as to represent the motions of the stars. To keep the proportions right, the speed of the stars must of course be reduced in the same proportion as the linear dimensions of the model. In this the earth's

yearly journey round the sun of 600 million miles had become reduced to a pin-head a sixteenth of an inch in diameter, or, say, a fifth of an inch in circumference. As the stars move through space with roughly the same speed as the earth in its orbit, we may suppose the yearly journey of each speck of dust in our model also to be about a fifth of an inch. Thus each speck of dust will move about an inch in five years, roughly 16 feet in a thousand years—or say a ten-millionth part of a snail's pace. If two specks started moving directly towards one another from opposite ends of Waterloo Station it would take them about 40,000 years to meet. For how long must six particles of dust, floating blindly about in the station, move at this pace before each has experienced enough close meetings with other specks of dust for their energy of motion to become thoroughly redistributed?

The mathematician, carrying out exact calculations with respect to the actual weights, speeds and distances of the stars, finds that the observed degree of approximation to equipartition of energy is such as gravitational interaction would have produced after action enduring through millions of millions of years, most probably from 5 to 10 millions of millions of years. This, then, ought, to all appearances, to be the length of life of the stars.

It is a stupendous length of time, and before finally accepting it we may well look for confirmation from other sources. In estimating the age of the earth we were able to invoke assistance from all kinds of clocks, astronomical, geological and physical; happily they all told much the same story. In the problem of estimating the ages of the stars, only astronomical clocks are available, but fortunately there are no fewer than three of these, and happily we shall find that all three agree in saying much the same thing.

THE ORBITS OF BINARY SYSTEMS. We have already seen (p. 48) how the two constituents of a binary system permanently describe closed elliptical orbits about one another, because neither can escape from the gravitational hold of its companion. Energy can reside in the orbital motion of these systems, as well as in their motion through space. And strict mathematical analysis shews that a long succession of gravitational pulls from passing stars must finally result in equipartition of energy, not only between the energies of motion of one system and another through space, but also between the various orbital motions of which each binary system is capable. When this final state of equipartition is ultimately reached, the orbits of the systems will not all be similar, but it can be shewn that their shapes will be distributed according to a quite simple statistical law. The orbits are of course ellipses (p. 48), and the law in question is such that all values for the ratio of the lengths of the axes are equally frequent*. As the orbits of actual systems are not found to conform to this law, it is clear that the stars have not yet lived long enough to attain equipartition of energy in respect of their orbital motions. It is impossible to discuss how far they have travelled along the road to equipartition without knowing the point, or points, from which they started.

The question of the origin of binary systems will be discussed more fully in the next chapter. For the moment it may be said that they appear to come into being in two distinct ways.

Practically all astronomical bodies are in a state of rotation about an axis. The earth rotates about its axis once every 24 hours, and Jupiter once every 10 hours,

* In more mathematical language, the eccentricity of orbit e is distributed in such a way that all values of e^2 from $e^2 = 0$ to $e^2 = 1$ are equally probable.

as is shewn by the motion of the red spot and other markings on its surface. The surface of the sun rotates every 25 days or so—we can follow its rotation by watching sun-spots, faculae and other features moving round and round its equator—although there are theoretical grounds for supposing that the sun's central core may rotate considerably faster than this, possibly performing a complete rotation in comparatively few days. And it is likely that all the other stars in the sky are also in rotation, some fast and some slow. We shall see later how, with advancing age, a star is likely to shrink in size, and this shrinkage generally causes its speed of rotation to increase. Now mathematical theory shews that there is a critical speed of rotation which cannot be exceeded with safety. If the star rotates too fast for safety, it simply bursts into two, much as a rotating fly-wheel may burst if it is driven at too high a speed. It is in this way that one class of binary stars come into being. With a few exceptions this class is identical with the class of spectroscopic binaries described in Chapter I (p. 58); the two component stars are generally too close together to appear as distinct spots of light in the telescope, only spectroscopic evidence telling us that we are dealing with two distinct bodies.

Another class of binaries, the visual binaries, which appear quite definitely as pairs of spots of light in the telescope, probably have a different origin. We shall see later how the stars first come into being as condensations of nebulous gas, a whole shoal being born when a single great nebula breaks up. It must often happen that adjacent condensations are so near as to be unable to elude each other's gravitational grip. In time these shrink down into normal stars, while the gravitational forces remain just as powerful as before, so that the final product is a pair of stars which must permanently journey through space in double harness,

because they have not energy of motion enough ever to get clear of one another's gravitational hold. This mechanism produces a class of binaries which is precisely similar to that formed by the break-up of single stars, except for an enormous difference in scale. The distance between the two components of such a system must be comparable with the original distance between separate condensations in the primaeval nebula out of which the stars were born; this is enormously greater than the corresponding distance in spectroscopic binaries, which is comparable only with the diameter of an ordinary star which has broken into pieces. This explains why visual binaries appear as distinct pairs of spots of light, while spectroscopic binaries do not.

In the final state of equipartition of energy, the shapes of the orbits will, as we have seen, be distributed according to a definite statistical law, and this law happens to be the same for all sizes of orbit. On the other hand, the time needed for equipartition of energy to bring this law about is not the same for all sizes of orbits; it is far greater for the compact orbits of the spectroscopic binaries than for the more open orbits of the visual binaries. The reason for this is that changes in the shape of an orbit are not caused by the gravitational pull of a passing star on the binary system as a whole, but rather by the *difference* of the gravitational pulls on the two components of the binary separately. If the two components are very close together, the passing star exerts practically the same forces on both. These forces affect the motions of the two components in precisely the same way, with the result that the motion of the binary system as a whole through space is changed, but the shape of orbit remains unaltered. The passing star gets a grip on the motion of the binary as a whole, but none on the orbits

of the components. On the other hand, when the components are far apart, the gravitational forces acting on the two may be widely different, so that a substantial change in the shape of the orbit may result, even if the encounter is not a very close one. In visual binaries, in which the components are usually hundreds of millions of miles apart, the time necessary to establish the final distribution of the shapes of the elliptical orbits is once again found to be of the order of millions of millions of years, but it is something like a hundred times as great as this for the far more compact spectroscopic binaries.

The following table, compiled from material given by Dr Aitken of Lick Observatory, shews the observed distribution of eccentricities in the orbits of those binaries for which accurate information is available:

The Approach to Equipartition of Energy in Binary Orbits

Eccentricity of Orbits	Observed number of spectroscopic binaries	Observed number of visual binaries	Number to be expected theoretically when the final state is attained
0 to 0·2	78	7	6
0·2 ,, 0·4	18	18	18
0·4 ,, 0·6	16	28	30
0·6 ,, 0·8	6	11	42
0·8 ,, 1·0	1	4	54

Let us look first at the spectroscopic binaries. In the observed orbits, we see that low eccentricities predominate, no fewer than 78 out of 119 having an eccentricity of less than one-fifth. In other words, most spectroscopic binaries have nearly circular orbits. Both theory and observation shew that when a star first divides up into a spectroscopic binary, the orbits of the two components must be nearly circular, so that the

table of observed orbits provides very little evidence of any progressive change of shape in the orbits as a whole. In contrast to this, the last column of the table shews the proportion of orbits of different eccentricities which is to be expected when, if ever, equipartition of energy is finally attained. Here high eccentricities, representing very elongated orbits, predominate; only one orbit in twenty-five is so nearly circular as to have an eccentricity less than a fifth.

In general the observed numbers tabulated in the second column shew no resemblance at all to the theoretical numbers tabulated in the fourth column. In other words, the spectroscopic binaries shew no suggestion of any near approach to the final state, most of them retaining the low eccentricity of orbit with which they started life. We should naturally expect this, since we have seen that hundreds or even thousands of millions of millions of years would be needed for these orbits to attain a final state of equipartition, and the stars cannot be as old as this, for if they were, their motions through space ought to shew absolutely perfect equipartition, which they certainly do not.

Turning now to the third column, we see that the visual binaries shew a good approach to the theoretical final state up to an eccentricity of about 0·6, but not beyond. The deficiency of orbits of high eccentricity may mean that gravitational forces have not had sufficient time to produce the highest eccentricities of all, but part, and perhaps all, of it must be ascribed to the simple fact that orbits of high eccentricity are exceedingly difficult to detect observationally and to measure accurately. Indeed, Russell has recently attempted a study of the eccentricity of visual binaries of very long periods, and from the rather uncertain evidence available, concludes that 500 systems with an average period of about 2000 years have an average

eccentricity of 0·61, while 800 with even longer periods, averaging perhaps 5000 years, have an average eccentricity of 0·76. Here obviously are orbits of large eccentricity to fill in the deficiencies in our table. It may be added that if equipartition of energy were ever fully established, the average eccentricity of all orbits ought to be exactly ⅔, or 0·67. Thus Russell's figures suggest that stars in which the constituents are far apart (for this is what long periods mean) may shew a fairly close approach to equipartition of energy in their orbital motions. This is precisely what we should expect, since such orbits are specially susceptible to the gravitational action of passing stars.

Clearly, then, the study of orbital motions, like that of motions through space, points to gravitational action extending over millions of millions of years. In each case there is an exception to "prove the rule." In the case we have just considered it is provided by the spectroscopic binaries, which are so compact that their constituents can defy the pulling-apart action of gravitation; in the former case it was provided by the *B*-type stars, which are so massive, possibly also so young, that the gravitational forces from less weighty stars have not yet greatly affected their motion.

When these two lines of evidence are discussed in detail, they agree in suggesting that the general age of the stars is about that already stated, namely, from five to ten millions of millions of years.

MOVING CLUSTERS. A third line of evidence, which also tells much the same story, may be briefly mentioned. The conspicuous groups of bright stars in the sky, such as the Great Bear, the Pleiades and Orion's Belt, consist for the most part of exceptionally massive stars which move in regular orderly formation through a jumble of slighter stars, like a flight of swans through

a confused crowd of rooks and starlings. Swans continually adjust their flight so as to preserve their formation. The stars cannot, so that their orderly formation must in time be broken by the gravitational pull of other stars. The lighter stars are naturally knocked out of formation first, while the most massive stars retain their formation longest. Observation suggests that this is what actually happens to a moving star-cluster; at any rate the stars which remain in formation generally have weights far above the average. And, as we can calculate the time necessary to knock out the lighter stars, we can at once deduce the ages of those which are left in. This again proves to be of the order of millions of millions of years.

The stars which are left in the moving cluster are of course still subject to the gravitational pull of the remainder of the stars. Although these pulls may not be adequate to knock the massive stars out of the clusters, they will nevertheless have an appreciable effect on their motion. We shall discuss this effect later (p. 235), and shall see that it must ultimately result in the surviving stars of the cluster assuming the flat shape of a biscuit or a watch, its diameter being roughly 2½ times its thickness. Now the more conspicuous moving clusters of the sky have already attained this shape or a reasonably close approximation to it. Again we can calculate how long it would take for this to come about, and again we find a time of the order of millions of millions of years.

Thus, the study of moving clusters provides a double method for estimating the ages of the stars. It confirms the three estimates already mentioned, so that we find that the three available astronomical clocks all tell much the same time. They agree in indicating an age of the order of five to ten millions of millions of years for the stars as a whole.

Another line of investigation, to be mentioned later (p. 207), again points to a similar age.

It is perhaps a little surprising that this age should prove to be so much longer than the two thousand million years or so which seems to be the most probable age of the earth, although there is of course no positive reason why the earth should not have been born during the last few moments of the lives of the stars. We must, however, remember that the facts to be correlated are not merely the ages of the earth and stars deduced from observation; there is the further fact that there are sentient beings on earth to observe them. If we suppose, as a pure conjecture, that no planet can support life for more than a few thousand million years, then the facts fall into order at once, and two thousand million years seems a highly reasonable age for our observing platform, regardless of the far greater ages of the stars.

It is much more disconcerting that our stellar ages prove to be so much longer than the hundred thousand million years or so which the Friedmann-Lemaître cosmology indicates as the maximum possible age of the universe. The universe seems to be far younger than the stars which constitute it! If we accept the apparent velocities of recession of the most distant nebulae as real, we find that a very few thousands of millions of years of motion at their present speeds would just about account for their present distances from us, so that a few thousands of millions of years ago, the nebulae must have been far more huddled together than they now are. This is of course very different from saying that the time which has elapsed since the creation of the nebulae can only be a few thousands of millions of years, yet we might reasonably have expected *à priori* that the two periods would be at least comparable.

To state the difficulty in a slightly different form, a period of two thousand million years seems to have made a great deal of difference to the earth, and if the apparent speeds of nebular motion are real, it has made a great deal of difference to the general arrangement in space of the great nebulae, so that it is odd that it should make so little difference to the stars that we need to postulate an age a thousand times as great before we can explain their present condition.

These considerations obviously suggest that the estimate just made of stellar ages should be accepted with caution and perhaps even with suspicion. Yet if we reject them, many facts of astronomy are left up in the air without any explanation, and much of the fabric of astronomy is thrown into disorder.

If, on the other hand, we accept them, and assign ages of millions of millions of years to the stars, we have to discard the Friedmann-Lemaître cosmology, which no longer provides sufficient time for the evolution of the stars, and fall back on one or other of the two cosmologies of de Sitter described on p. 101. These fix no definite limit to the past ages of the stars, although both require that only a few thousands of millions of years ago the disposition of the universe must have been very different from what it is now. This is rather unexpected, but can hardly be counted as an objection to them. Indeed, it goes far towards disposing of the two rather vague difficulties mentioned on p. 193. It also removes a difficulty which Eddington and others have felt as to the rotation of the galaxy. The difficulty is to see how the galactic system can have been rotating for millions of millions of years at the comparatively rapid rate of about four revolutions every thousand million years, without acquiring a more regular structure than it appears to have. The answer provided by the de Sitter

cosmologies is that present conditions did not have their origin millions of millions of years ago, but only a few thousands of millions of years ago.

Thus it appears that the only schemes at present in the field against which no really fatal objections can be urged are to be found in the two cosmologies of de Sitter described on p. 101. We have to suppose that the stars have existed through the millions of millions of years needed for their energies to approach nearly to a state of equipartition, while the universe has been either pulsating or else undergoing a single contraction followed by the present expansion. Einstein appears to prefer the pulsating universe, while de Sitter at present (Sept. 1933) advocates the latter alternative, but I doubt whether anyone would claim that either solution is likely to prove final. The field is too vast, too novel, and too unexplored for anyone to assert that all its possibilities are already known.

STELLAR RADIATION

Whatever ages we finally assign to the stars, one particular star, our sun, must be at least as old as the earth, and it is impossible to assign an age of much below two thousand million years to this. Throughout the whole of this period, and possibly for some hundreds or thousands of times longer, the sun has in all probability been pouring out light and heat at least as profusely as at present. Indeed, a mass of evidence, to which we shall return later, shews that young stars emit more radiation than older stars, so that during most of its long life the sun must have been pouring out energy even more lavishly than now.

If our ancestors thought about the matter at all, they probably saw nothing remarkable in this profuse outpouring of light and heat, particularly as they had no conception of the stupendous length of time during

which it had lasted. It was only in the middle of last century, when the principle of conservation of energy first began to be clearly understood, that the source of the sun's energy was seen to constitute a scientific puzzle of really first-class difficulty. The sun's radiation obviously represented a loss of energy to the sun, and, as the principle of conservation shewed that energy could not originate out of nothing, this energy necessarily came from some source or store adequate to supply vast outpourings of energy over a very long period of time. Where was such a store to be found?

The sun at present pours out radiation at such a rate that if the necessary energy were generated in a power-station outside the sun, this station would have to burn coal at the rate of many thousands of millions of millions of tons a second. There is of course no such power-station. The sun is entirely dependent on its own resources; it is a ship on an empty ocean. And if, like such a ship, the sun carried its own store of coal, or if, as Kant imagined, its whole substance were its store of coal, so that its light and heat came from its own combustion, the whole would be burnt into ashes and cinders in a few thousand years at most.

The history of science records one solitary attempt to explain the sun's energy as coming in from outside. We have seen how the energy of motion of a bullet is transformed into heat when the speed of the bullet is checked. An astronomical example of the same effect is provided by the familiar phenomenon of shooting-stars. These are bullet-like bodies which fall into the earth's atmosphere from outer space. So long as such a body is travelling through empty space, its fall towards the earth continually increases its speed, but, as it enters the earth's atmosphere, its speed is checked by air-resistance, and the energy of its motion is gradually transformed into heat. The shooting-star becomes first

hot and then incandescent, emitting the bright light by which we recognise it. Finally, it is completely vaporised by its own heat, and disappears from sight, leaving only a momentary trail of luminous gas behind. The original energy of motion of the shooting-star has been transformed into light and heat—the light by which we see it, and the heat by which it is ultimately vaporised.

In 1849 Robert Mayer suggested that the energy which the sun emitted as radiation might accrue to it from a continuous fall of shooting-stars or similar bodies into the solar atmosphere. The suggestion is untenable, because a simple calculation shews that a mass of such bodies equal to the weight of the whole earth would hardly maintain the sun's radiation for a century, and that the infall needed to maintain the sun's radiation for 30 million years would double its weight. As it is quite impossible to admit that the sun's weight can be increasing at any such rate, Mayer's hypothesis has to be abandoned.

In 1853 Helmholtz put forward a very similar theory, the famous "contraction-hypothesis" according to which the sun's own shrinkage sets free the energy which ultimately appears as radiation. If the sun's radius shrinks by a mile, its outer atmosphere falls through a height of a mile and sets free as much energy in so doing as would be yielded up by an equal weight of shooting-stars falling through a mile and having their motion checked. On Helmholtz's theory, the different parts of the sun's own body performed the *rôles* which Mayer had allotted to shooting-stars falling in from outside; they performed these same parts again and again, until ultimately the sun had shrunk so far that it could shrink no further. This theory also failed to survive the test of numerical computation. In 1862 Lord Kelvin calculated that the shrinkage of the sun

always run through the hour-glass at the same rate. The rate at which the sun loses weight will not vary appreciably between to-day and to-morrow, or even over a century or a million years, but we must be on our guard against going too far. If the sun continued to radiate at precisely its present rate until it had turned absolutely the whole of its present mass into radiation, a simple sum in division shews that it would last for just about 15 million million years, by which time its last ounce of weight would be disappearing. Incidentally this gives us a vivid conception of the enormous weight of the sun; it could go on pouring away its substance into space at 650 times the rate at which water is pouring over Niagara for 15 million million years before becoming exhausted.

Obviously, however, we cannot carry out our calculations in this simple light-hearted way; it would be absurd to suppose that the sun's last ton of substance will radiate energy at the same rate as his present stupendous mass of two thousand million million million million million tons. A series of investigations, which culminated in a paper published by Eddington in 1924, disclosed that, in a general sort of way, a star's luminosity depends mainly on its weight. The dependence is not very precise, and neither is it universal, but when we are told a star's weight we can say that its luminosity is likely, with a high degree of probability, to lie within certain fairly narrow limits. For instance, most stars whose weight is nearly equal to the sun are found to have about the same luminosity as the sun. In general, as might be expected, stars of light weight radiate less than heavy stars, but also—and this could not have been foreseen—the differences in their radiations are far greater than the differences in their weights. The law which we have already (p. 51) found to hold for a few stars in the neighbourhood of the sun is true, although in

to its present size could hardly have provided energy for more than about 50 million years of radiation in the past, whereas the geological evidence already noticed (p. 169) shews that the sun must have been shining for a period enormously longer than this.

To track down the actual source of the sun's energy with any hope of success, we must give up guessing, and approach the problem from a new angle. We have seen (p. 138) how radiation carries weight about with it, so that any body which is emitting radiation is necessarily losing weight; the radiation emitted by a searchlight of 50 horse-power would, we saw, carry away weight at the rate of about a twentieth of an ounce a century. Now each square inch of the sun's surface is in effect a searchlight of just about 50 horse-power, whence we conclude that weight is streaming away from every square inch of the sun's surface at the rate of about a twentieth of an ounce a century. Such a loss of weight seems small enough, until we multiply it by the total number of square inches which constitute the whole surface of the sun. It then appears that the sun as a whole is losing weight at the rate of rather over 4 million tons a second, or about 250 million tons a minute—something like 650 times the rate at which water is streaming over Niagara.

THE PAST HISTORIES OF THE SUN AND STARS. Let us carry on the multiplication. Two hundred and fifty million tons a minute is 360,000 million tons a day. Thus the sun must have weighed 360,000 million tons more than now at this time yesterday, and will weigh 360,000 million tons less at this time to-morrow. And 360,000 million tons a day is 131 million million tons a year. We can dig as far into the past as we like in this way and can probe as far as we like into the future. But soon we encounter the usual trouble which besets all calculations of this kind—the sand does not

always run through the hour-glass at the same rate. The rate at which the sun loses weight will not vary appreciably between to-day and to-morrow, or even over a century or a million years, but we must be on our guard against going too far. If the sun continued to radiate at precisely its present rate until it had turned absolutely the whole of its present mass into radiation, a simple sum in division shews that it would last for just about 15 million million years, by which time its last ounce of weight would be disappearing. Incidentally this gives us a vivid conception of the enormous weight of the sun; it could go on pouring away its substance into space at 650 times the rate at which water is pouring over Niagara for 15 million million years before becoming exhausted.

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a somewhat different sense, for the stars as a whole—the candle-power per ton is greatest in the heaviest stars.

For example, the average star of half the weight of the sun does not radiate anything like half as much energy as the sun: the fraction is more like an eighth. This consideration extends the future life of the sun, and indeed of all the stars, almost indefinitely. For if we imagine the stars to live so long that their weights become appreciably less than now, they will radiate less energetically than now and in this way conserve their resources. A sort of parsimony will creep over them in their old age; so long as they have plenty of weight to squander, they squander it lavishly, but they will contract their scale of expenditure when they have little left to spend. The sand runs slowly through the hour-glass when there is little left to run.

In the same way, the average star of double the sun's weight does not merely radiate twice as much energy as the sun; it radiates about eight times as much. We must keep this in view in estimating the past life of the sun; it shortens the maximum past life that we can assign to the sun just as surely as the opposite effect lengthens its future life. Observation tells us at what rate the average star of any given weight spends its weight in the form of radiation, and, on the supposition that the sun has behaved like this typical average star at the corresponding stage of its own past history, we can draw up a table exhibiting its gradual change of weight as its life progressed. Selected entries from this table would read somewhat as follows:

2,000,000,000	years ago,	the sun had	1·00013	times its	present weight
1,000,000,000,000	,,	,,	1·07	,,	,,
2,000,000,000,000	,,	,,	1·16	,,	,,
5,700,000,000,000	,,	,,	double		,,
7,100,000,000,000	,,	,,	4 times		,,
7,400,000,000,000	,,	,,	8 ,,		,,
7,500,000,000,000	,,	,,	20 ,,		,,
7,600,000,000,000	,,	,,	100 ,,		,,

The first entry represents roughly the time since the earth was born. It shews that, during the whole existence of the earth, the sun's weight has changed by only an inappreciable fraction of the whole. Consequently, it seems likely, although naturally we cannot be certain, that when the earth was born the sun was much the same as it now is, and that it has been the same, in all essential respects, throughout the whole life of the earth.

To come to appreciably different conditions we have to go back to remote aeons far beyond the time of the earth's birth. We are free to do this, conjecturally at least, since our estimates of stellar ages have suggested that the earth's whole life is only a moment in the lives of the stars. We have estimated the latter as being something of the order of 5 to 10 million million years, and it is only when we go back an appreciable fraction of these long periods that we find the sun's weight differing appreciably from its present weight. We have, for instance, to go back more than 5 million million years to find the sun with double its present weight. When we go back much farther than this a new phenomenon appears; the weight of our hypothetical past sun begins to go up by leaps and bounds. In time it begins to double and more than double every 100,000 million years, and we cannot go back as far as 8 million million years without postulating a sun of quite impossibly high weight. The sun must, then, have been born some time within the last 8 million million years.

The exact figures of our table may be open to suspicion, but as a general fact of observation there is no doubt that very massive stars radiate away their energy, and therefore also their weight, with extraordinary rapidity. Indeed, the process is so rapid that we may disregard all that part of a star's life in which it has more than about 10 times the weight of the

sun—this is lived at lightning speed. Apart from all detailed calculations, this general principle fixes a definite limit to the ages, not only of the sun, but also of every other star. The upper limit to the age of the sun is certainly somewhere in the neighbourhood of 8 million million years.

This agrees well enough with the general age of from 5 to 10 million million years that other calculations have assigned to the stars in general. The calculations thus reinforce one another, and it begins to look as if at least two of the pieces of the puzzle were going to fit satisfactorily together.

Unfortunately, difficulties emerge as soon as we discuss the ages of exceptionally massive stars—stars which at present have many times the weight of the sun. The table on p. 182 shews that stars of a certain class (spectral type *A* 0) with six times the weight of the sun have motions in space which conform well enough to the law of equipartition of energy. Unless this is a pure coincidence (and this is unlikely, in view of the fact that other groups of only slightly less weight conform equally well), we must assign an age of from 5 to 10 million million years to these very massive stars. Yet the average star of this weight is emitting about a hundred times as much radiation as the sun, which means that it is halving its weight every 150,000 million years. Clearly this process cannot have gone on for anything like 5 or 10 million million years.

Still more luminous stars present the problem in an even more acute form. The star *S* Doradus in the Lesser Magellanic Cloud is at present emitting 300,000 times as much radiation as the sun. Whereas the sun is pouring its weight out into space at the rate of 650 Niagaras, *S* Doradus is pouring it out at the rate of 200,000,000 Niagaras; every 50 million years it loses a weight equal to the total weight of the sun. It is

obviously absurd to imagine that this star can have been losing weight at this rate for millions of millions of years; indeed, its present rate of loss of weight would seem to limit its age to something comparable with the age of the earth.

For such a star as *S* Doradus only two alternatives seem open. Either it was created quite recently (on the astronomical time-scale), and so is still at the very beginning of its prodigal youth, or else its loss of weight has in some way been inhibited through the greater part of its life. A good many arguments weigh against the hypothesis of recent creation. The star is a member of a star cloud in which we should naturally expect all the members to be of approximately equal age. It is in a region of space in which there are no indications that stars are still being born. And, even if we accept the hypothesis of recent creation for any particular star or stars, we are still at a loss to explain how the other massive stars, which figure in the table on p. 182, can be old enough for equipartition of energy to have become already established.

For many reasons it seems preferable, and indeed almost inevitable, to suppose that these highly luminous and very weighty stars have in some way been saved from energetic radiation, with its consequential rapid wasting of weight, throughout the greater part of their lives. In brief, we suppose that they are cases of arrested development, whose weight and general appearance equally belie their true ages. Later (p. 338) we shall come upon a physical mechanism which may perhaps explain how this could happen.

The exceptionally luminous stars which we have just had under discussion are comparatively rare objects in the sky. The vast majority of stars have luminosities and weights comparable with, or distinctly less than, those of the sun, and for these the difficulty does not

exist. Indeed, the hypothesis of arrested development would break down under its own weight if we had to invoke its help for many stars; we should then be led to the absurd conclusion that the stars as a whole happened to be exceptionally bright at the present moment in the history of the universe. The hypothesis is tenable just because we seldom need to use it.

If this hypothesis can be accepted, we become free to assign any age we please to the stars, and naturally select that indicated by the law of equipartition of energy, at any rate for those classes of stars which are found to conform to this law.

THE SOURCE OF STELLAR ENERGY

The ages of millions of millions of years which we are now tentatively assigning to the stars imply that at birth the sun must have had at least double, and more probably several times, its present weight. For every ton which existed in the sun at its birth only a few hundredweight remain to-day. The rest of the ton has been transformed into radiation and, streaming away into space, has left the sun for ever.

In the preceding chapter we had occasion to discuss the transformation of weight into radiation which accompanies the spontaneous disintegration of radioactive atoms. The most energetic instance of this phenomenon known on earth is the transformation of uranium into lead, in which about one part in 4000 of the total weight is transformed into radiation. Thus, if the sun were originally formed of pure uranium, it would be able to discharge this fraction of its weight as radiation, and this would maintain the sun's radiation at its present strength for rather less than four thousand million years. Yet for a more massive star the period would be less, and we very soon fall below

the two thousand million years or so which is the known age of the earth. Thus, it seems safe to conclude that the process by which the sun and stars generate their light and heat must involve a far more energetic transformation of material weight into radiation than any process known on earth.

Perrin and Eddington at one time suggested that this process may be the building up of complex atomic nuclei out of protons and electrons. The simplest, and most favourable example of this, which was especially considered by Eddington, is to be found in the building up of the helium nucleus. The constituents of a helium atom are precisely identical with those of four hydrogen atoms, namely, four electrons and four protons. If these constituents could be re-arranged without any transformation of material weight into radiation, the helium atom would have precisely four times the weight of the hydrogen atom. In actual fact Aston finds that the ratio of weights is only 3·970. The difference between this and 4·000 represents the weight of the radiation which must be emitted when, if ever, the helium atom is built up by the coalescence of four hydrogen atoms. The loss of weight, one part in 130, is very much greater than occurs in radio-active transformations, but even so it can hardly be said to provide adequate lives for the stars. The transformation of a sun which originally consisted of pure hydrogen into one consisting wholly of helium would only provide radiation at the sun's present rate of radiation for about 100,000 million years, and when we pass to more massive stars, the familiar difficulties recur. The most massive stars of all radiate more than 5000 times as much energy per ton of their mass as the sun, so that for them this source of energy would provide radiation for less than two thousand million years, which again is less than the known age of the earth.

THE ANNIHILATION OF MATTER. Modern physics is only able to suggest one process capable of providing a sufficiently long life for a radiating star; it is the actual annihilation of matter. Various lines of evidence suggest that the atoms in very massive stars are not, for the most part, fundamentally different from those in less massive stars. In particular, we have seen (p. 54) that the atmospheres of all stars, no matter how different they may appear in the spectroscope, probably consist of much the same types of atoms occurring in much the same proportions, and it is reasonable to suppose that this similarity extends down into the star's interior. If so, the primary cause of the difference in weight between a heavy star and a light star is not a difference in the quality of the atoms of which the star is formed; it is a difference in their number. A heavy star can only change into a light star through the actual disappearance of atoms; these must be annihilated, and their weight transformed into radiation.

I first drew attention in 1904 to the large amount of energy capable of being liberated by the annihilation of matter, positive and negative electric charges rushing together, annihilating one another and setting their energy loose in space as radiation. The next year Einstein's theory of relativity provided a means for calculating the amount of energy which would be produced by the annihilation of a given amount of matter; it shewed that energy would be set free at the rate of 9×10^{20} ergs per gramme, regardless of the nature or condition of the substance which is annihilated. The length of life which this source of energy permits to the stars is, generally speaking, precisely the millions of millions of years which dynamical theory demands. This suggests that the actual annihilation of matter may form the true source of stellar energy.

One consequence of this supposition may be men-

tioned at once, because its fulfilment or non-fulfilment provides a test of the truth of the supposition. We have already mentioned that, generally speaking, the "candle-power per ton of weight" is greatest in the heavier stars. As an immediate consequence the loss of weight per ton is greatest in the heaviest stars. A massive star may lose a hundredweight per ton, in a period of time in which a star of light weight loses only a few pounds per ton. The consequence is that the passage of time tends to equalise the weights of the stars. This principle may perhaps explain in large part why the present stars shew no very great range of weight. It also leads to interesting consequences when applied to the two components of a binary system. It shews that as a binary system ages, its two components ought continually to become more nearly equal in weight. Thus the two components ought to differ less in weight in old binaries than in young.

This last conclusion can be tested observationally. As regards spectroscopic binaries, Aitken finds that the ratio of weights of the two constituents of a binary increases from about 0·70 for systems of large weight to 0·90 for systems in which the constituents are about similar to the sun. The direction of change is that predicted by theory, and if it is the result of the loss of weight by radiation, the amount of change indicates a time-interval of the order of millions of millions of years between the two states concerned. Other astronomers have studied the corresponding problems presented by eclipsing and visual binaries, and have reached almost identical conclusions. The predictions of theory seem to be confirmed by each type of binary system separately.

We must not overlook the revolutionary nature of the change which this hypothesis introduces into physical science. The two fundamental corner-stones of nineteenth-century physics, the conservation of

matter and the conservation of energy, are both abolished, or rather are replaced by the conservation of a single entity which may be matter and energy in turn. Matter and energy cease to be indestructible and become interchangeable, according to the fixed rate of exchange of 9×10^{20} ergs per gramme.

Yet, looked at from another angle, the hypothesis only carries physics one stage farther along the road it has already trodden in the past. Heat, light, electricity have all in turn proved to be forms of energy; the annihilation hypothesis only proposes to add another to the list, so that matter itself also becomes a form of energy. And if the transitory existence of the positron, mentioned on p. 208, is confirmed by fuller research, experimental confirmation of the hypothesis will have been obtained in our laboratories. Further investigations on cosmic radiation may in time provide additional confirmation, in the way suggested on p. 167.

According to this hypothesis all the energy which makes life possible on earth, the light and heat which keep the earth warm and grow our food, and the stored-up sunlight in the coal and wood we burn, if traced far enough back, are found to originate out of the annihilation of electrons and protons in the sun. The sun is destroying its substance in order that we may live, or, perhaps we should rather say, with the consequence that we are able to live. The atoms in the sun and stars are, in effect, bottles of energy, each capable of being broken and having its energy spilled throughout the universe in the form of light and heat. Most of the atoms with which the sun and stars started their lives have already met this fate; the remainder are probably destined to meet it in time. Scientific writers of half a century ago delighted in the picturesque description of coal as "bottled sunshine"; they asked us to think of the sunshine as being bottled up as it fell on the

vegetation of the primaeval jungle, and stored for use in our fireplaces after millions of years. On the hypothesis we are now considering, we must think of it as re-bottled sunshine, or rather re-bottled energy. The first bottling took place millions of millions of years ago, before either sun or earth was in being, when the energy was first penned up in protons and electrons. Instead of thinking prosaically of our sun as a mere collection of atoms, let us think of it for a moment as a vast storehouse of bottles of energy which have already lain in storage for millions of millions of years. So enormous is the sun's supply of these bottles, and so great the amount of energy stored in each that, even after radiating light and heat for 7 or 8 million million years, it still has enough left to provide light and heat for millions of millions of years yet to come.

Two quantitative considerations may help to shew these processes in a clearer light. We have seen that the sun's present store of atoms would, at the present rate of breakage, last for 15 million million years. This means that every year only one atom in 15 million million is broken, a fraction which may seem absurdly small to produce the sun's continuous outpourings of energy at the rate of about 50 horse-power per square inch. Let us, however, reflect that the energy which is continually pouring out of the sun's surface is generated throughout the whole vast interior of the sun's body; the stream of energy which emerges from a square inch of surface is the concentration of all the energy generated in a cone of a square inch cross-section, but of 433,000 miles depth. Such a cone contains about 10^{33} atoms, and although only one in 15 million million is broken each year, there are still about two million million atoms destroyed each second.

Even so, the amount of energy set free by the

annihilation of matter is rather surprising; it is of an entirely different order of magnitude from that made available by any other treatment. The combustion of a ton of the best coal in pure oxygen liberates about 5×10^{16} ergs of energy; the annihilation of a ton of coal liberates 9×10^{26} ergs, which is 18,000 million times as much. In the ordinary combustion of coal we are merely skimming off the topmost cream of the energy contained in the coal, with the consequence that 99·999999994 per cent. of the total weight remains behind in the form of smoke, cinders or ash. Annihilation leaves nothing behind; it is a combustion so complete that neither smoke, ash, nor cinders is left. If we on earth could burn our coal as completely as this, a single pound would keep the whole British nation going for a fortnight, domestic fires, factories, trains, power-stations, ships and all; a piece of coal smaller than a pea would take the *Mauretania* across the Atlantic and back.

Purely astronomical evidence has suggested that atoms are continually being annihilated in the sun and stars. Here we have a piece of the puzzle which may perhaps be found to fit on to those we tentatively fitted together in the last chapter. As we there saw, recent investigations in mathematical physics suggest that the highly penetrating radiation received on earth may quite possibly have its origin in the annihilation of matter out in space. And the amount of this radiation received on earth is so great that we had to suppose the underlying annihilation of matter to be one of the fundamental processes of the universe; we now discover that it may well be the process which keeps the sun and stars shining and the universe alive.

PHYSICAL INTERPRETATION. It is perhaps worth trying to probe still one stage farther into the physical nature of this process of annihilation of matter, although

it must be premised that what follows is speculative in the sense that no direct observational confirmation is at present available.

We have seen (p. 152) how the electrodynamical theory current in the last century required that the nucleus and electron of the hydrogen atom should approach ever closer and closer to one another with the mere passage of time, until finally they rushed together and coalesced. When this happened, the negative charge of the electron and the positive charge of the nucleus would neutralise one another and their energy would go off in a flash of radiation similar to the flash of lightning which indicates that the negative and positive charges in two opposing thunderclouds have met and neutralised one another.

The more recent quantum theory calls a halt to this motion as soon as the nucleus and electron have approached to within a distance of $0{\cdot}53 \times 10^{-8}$ centimetre of one another, and by so doing keeps the universe in being as a going concern (p. 152). Other halts are also established at 4, 9, 16, etc. times this distance, but here the prohibition on farther progress is not absolute. At these longer distances the demand of the quantum theory "thus far shalt thou go and no farther" seems to be replaced by "thou shalt go no farther until after a long time." And it now seems possible, on the astronomical evidence, that the prohibition at the shorter distance may not be absolute either. From the physical end nothing is known for certain, although here again it seems contrary to the newer conceptions of physics, as embodied in the wave-mechanics, that any such absolute prohibition should exist, either for the hydrogen atoms or for other more complex atoms. Perhaps after waiting a long time in the orbit nearest to the nucleus, the electron is permitted, or even encouraged or compelled, to proceed; it merges itself into the nucleus and

a flash of radiation is born in a star. This provides the most obvious mechanism for the annihilation of electrons and protons which the evidence of astronomy seems to demand. It will, however, be clearly understood that this is a purely conjectural conception of the mechanism; we shall return to a further consideration of this very intricate problem in Chapter v.

If this conjecture should prove to be sound, not only the atoms which provide stellar light and heat, but also every atom in the universe, are doomed to destruction, and must in time dissolve away in radiation. The solid earth and the eternal hills will melt away as surely, although not as rapidly, as the stars:

> The cloud-capped towers, the gorgeous palaces,
> The solemn temples, the great globe itself,
> Yea, all which it inherit, shall dissolve,
> And...leave not a rack behind.

And if the universe amounts to nothing more than this, shall we carry on the quotation:

> We are such stuff
> As dreams are made on; and our little life
> Is rounded with a sleep,

—or shall we not?

CHAPTER IV

Carving out the Universe

We have now explored space to the farthest depths to which our telescopes can probe, and have explored into the intricacies of the minute structures we call atoms, of which the whole material universe is built. These in turn have proved to be formed of still more fundamental units—the minute charged particles we call protons and electrons, to which it may prove necessary to add the newly discovered neutron and positron. An unthinkably great number of these—according to Eddington's estimates about 10^{79} of each—have somehow fallen together to form a universe. They have not fallen into mere random chunks or agglomerations of matter, but into distinctive and characteristic formations—stars, nebulae, etc. It is natural to inquire why these special formations were formed rather than others.

We have commented on the surprising emptiness of space: six specks of dust in Waterloo Station about represent the extent to which it is occupied by stars in its most crowded parts. The comment might well have taken another form. Six specks of dust contain, let us say, a thousand million million molecules. Our model of space is empty because this great number of molecules happens all to be aggregated into as few as six lumps. In real space the unit of aggregation is the star, and an average star contains about 10^{56} molecules —a number so large that it is quite useless to try to imagine it. The emptiness of space does not originate from any paucity of molecules; it originates from the circumstance that, apart from those which form the tenuous clouds of gas stretching from star to star, the

molecules are aggregated together in the huge colonies we call stars, with about 10^{56} members to each. Why should the molecules in space herd together in this way, when the molecules in the rooms in which I am writing and you are reading do not?

Following a well-tried scientific method, we may attempt to discover why these aggregates have formed, by first examining what keeps them together now that they have formed. The earth's atmosphere consists of about 10^{44} molecules. Why do they stay pressed down into an atmosphere instead of spreading out through space? The answer is of course provided by the earth's gravitation. A bullet fired from the earth's surface with a speed of 6·93 miles a second or more will fly off into space, because the earth's gravitational pull is inadequate to hold it back when it moves with so high a speed. But a bullet fired with a speed of less than 6·93 miles a second does not leave the earth; its speed is inadequate to take it clear of the earth's pull. Thus the molecule-bullets which form the earth's atmosphere, which are almost all flying with speeds of less than a mile a second, have no chance at all of getting away. The earth's gravitation continually pulls them back to earth, and in this way the earth retains its covering of air.

At rare intervals a molecule may experience a succession of exceptionally lucky collisions with other molecules, and so attain a speed of more than 6·93 miles a second. A molecule which happens to arrive at the outside of the earth's atmosphere with such a speed will leave the earth altogether, and join the interstellar crowd of stray molecules. The earth is continually shedding a minute fraction of its atmosphere in this way, but calculation shews that the loss, even in millions of millions of years, is quite insignificant, so that we may regard the earth's atmosphere as permanent.

It is the same with the sun. The sun's heat has broken up the molecules of its atmosphere into their constituent atoms, and these move with an average speed of about 2 miles a second. But an atom-bullet would have to move at about 380 miles a second to escape altogether from the sun, so that again the solar atoms remain to form an atmosphere.

If all the molecules of air in an ordinary room were collected into a bunch at the centre of the room, the ball of air so formed would of course exert a gravitational pull on its outermost molecules, of the same kind as the earth and sun exert on the molecules of their atmospheres. But, because the weight of this ball of air is relatively so small, the intensity of its gravitational pull would also be small; indeed, it would be so feeble that a speed of about a yard an hour would be enough to take the outermost molecules clear of it. As the molecules of ordinary air move with an average speed of about 500 yards a second, such a ball of air would immediately scatter through the whole room. On the other hand, if the room were big enough to contain the sun, all its molecules could stay in a ball at the centre, just as they do in the sun. The outermost molecules would need a speed of at least 380 miles a second to escape, so that their actual speeds of 500 yards a second or so would be of no service to them.

PLANETARY ATMOSPHERES. In general the question of escape or no escape depends on the outcome of a battle between the molecular speeds of the outermost molecules, and the intensity of the gravitational hold which the remainder of the mass exerts on them. The solar system provides many examples of this. The moon has only a twenty-third as much gravitational hold over the molecules of an atmosphere as the earth has, with the result that any atmosphere the moon may ever have had, has escaped by now. Mercury has only

a tenth of the earth's gravitational hold, and also, owing to its nearness to the sun, its sunward surface is very hot, with the consequence that its atmosphere also has escaped. The gravitational hold of Mars on its molecules is only a fifth of the earth's, but its surface is cooler. Calculation shews that water-vapour and heavier molecules ought to remain, while the lighter molecules of helium and hydrogen ought to have escaped. This probably represents what has actually happened. The largest satellite of Saturn and the two largest satellites of Jupiter would exercise about the same gravitational hold as the moon, but as their surfaces must be enormously colder than that of the moon, they ought to be able to retain atmospheres. Some observers claim to have seen indications of atmospheres on all three satellites. All the four major planets exert stronger gravitational holds over their molecules than the earth, and so retain their atmospheres with ease, while Venus, with approximately the same gravitational hold as the earth, also retains an atmosphere.

These considerations amply explain why the molecules of the stars must necessarily remain aggregated now that the aggregates have once been formed, but the question of how and why these aggregates formed in the first instance is far more complex. What, for instance, determined that there should be about 10^{56} molecules in each star rather than 10^{54} or 10^{58}?

GRAVITATIONAL INSTABILITY

It is natural to enquire whether the forces which now keep a star together may not also have been responsible for its falling together in the first instance. This leads us to study the aggregating power of gravitation in some detail.

Five years after Newton had published his law of

gravitation, Bentley, the Master of Trinity College, wrote him, raising the question of whether the newly discovered force of gravitation would not account for the aggregation of matter into stars, and we find Newton replying, in a letter of date December 10, 1692:

> It seems to me, that if the matter of our sun and planets, and all the matter of the universe, were evenly scattered throughout all the heavens, and every particle had an innate gravity towards all the rest, and the whole space throughout which this matter was scattered, was finite, the matter on the outside of this space would by its gravity tend towards all the matter on the inside, and by consequence fall down into the middle of the whole space, and there compose one great spherical mass. But if the matter were evenly disposed throughout an infinite space, it could never convene into one mass; but some of it would convene into one mass and some into another, so as to make an infinite number of great masses, scattered great distances from one to another throughout all that infinite space. And thus might the sun and fixed stars be formed, supposing the matter were of a lucid nature.

An exact mathematical investigation on which I embarked in 1901 not only confirms Newton's conjecture in general terms, but also provides a method for calculating what size of aggregates would be formed under the action of gravitation.

THE FORMATION OF CONDENSATIONS. You stand in the middle of a room and clap your hands. In common language you are making a noise; the physicist, in his professional capacity, would say you are creating waves of sound. As your hands approach one another, they expel the intervening molecules of air. These stampede out, colliding with the molecules of outer layers of air, which are in turn driven away to collide with still more remote layers; the disturbance originally created by the motion of your hands is carried on in the form of a wave. Although the individual molecules

have an average speed of 500 yards a second, the zig-zag quality of their motions reduces the speed of the disturbance, as we have already seen, to about 370 yards a second—the ordinary velocity of sound. As the disturbance reaches any point, the number of molecules there becomes abnormally high, for the stampeding molecules add to the normal quota of molecules at the point. This of course produces an excess of pressure. It is this excess pressure acting on my ear-drum that transmits a sensation to my brain, so that I hear the noise of your clapping your hands.

This excess of pressure cannot of course persist for long, so that the excess of molecules which produces it must rapidly dissipate. It is thus that the wave passes on. Yet there is one factor which militates against its dissipation. Each molecule exerts a gravitation pull on all its neighbours, so that where there is an excess of molecules, there is also an excess of gravitational force. In an ordinary sound wave this is of absolutely inappreciable amount, yet such as it is, it provides a tiny force holding the molecules back, and preventing them scattering as freely as they otherwise would do. When the same phenomenon occurs on the astronomical scale, the corresponding forces may become of overwhelming importance.

Let us speak of the gas in any region of space where the number of molecules is above the average of the surrounding space, as a "condensation." Then it can be proved that, if a condensation is of sufficient extent, the excess of gravitational force may be sufficient to inhibit scattering altogether. In such a case, the condensation may continually grow through attracting molecules into it from outside, whose molecular speeds are then inadequate to carry them away again.

Whether this happens or not will depend of course on the speed of molecular motion in the gas, as well as

on the size of the condensation. But it will not depend at all on the extent to which the process of condensation has proceeded. By doubling the excess number of molecules in any condensation, we double the extent to which condensation has proceeded. In so doing, we double the gravitational pull tending to increase the condensation, but we also double the excess pressure which tends to dissipate it; we double the weights on each side of the balance, but the balance still swings in the same direction. If once conditions are favourable to its growth, a condensation goes on growing automatically until there are no further molecules left for it to absorb.

The greater the extent in space of a condensation, the more favourable conditions are to its continued growth. Other things being equal, a condensation two million miles in diameter will exert twice the gravitational force of a condensation one million miles in diameter, but the excess pressures are the same in the two cases. Thus, the larger a condensation is the more likely it is to go on growing, and by passing in imagination to larger and larger condensations we must in time come to condensations of such a size that they are bound to keep on growing. Nature's law here is one of unrestricted competition. Nothing succeeds like success, and so we find that condensations which are big to start with have the capacity of increasing still farther, while those which are small merely dissipate away.

Suppose now that an enormous mass of uniform gas extends through space for millions of millions of miles in every direction. Any disturbance which destroys its uniformity may be regarded as setting up condensations of every conceivable size.

This may not seem obvious at first; it may be thought that a disturbance which only affected a small area of gas would only produce a condensation of small extent.

Such an argument overlooks the way in which the gravitational pull of a small body acts throughout the universe. The moon raises tides on the distant earth, and also tides, although incomparably less in amount, on the most distant of stars. Each time the child throws its toy out of its baby-carriage, it disturbs the motion of every star in the universe. So long as gravitation acts, no disturbance can be confined to any area less than the whole of space. The more violent the disturbance which creates them, the more intense the condensations will be to begin with, but even the smallest disturbance must set up condensations, although these may be of extremely feeble intensity. And we have seen that the fate of a condensation is not determined by its intensity but by its size. No matter how feeble their original intensity may have been, the big condensations go on growing, the small ones disappear. In time nothing is left but a collection of big condensations. The mathematical analysis already referred to shews that there is a definite minimum weight such that all condensations below this weight merely dissipate away into space. This minimum weight is such that if approximately a tenth of this weight of gas were isolated in space, and all the rest of the gas annihilated, the molecules would just and only just fail to escape from its surface*.

We may say that the original uniformly distributed mass of gas was "unstable" because any disturbance,

* This is near enough, but not absolutely accurate. Exact mathematical analysis shews that the weight of the minimum condensation M is given by

$$M = \left(\tfrac{1}{3}\pi\kappa\right)^{\frac{3}{2}} \frac{C^3}{\gamma^{\frac{3}{2}}\rho^{\frac{1}{2}}}.$$

where C, γ, ρ, κ are the molecular velocity, gravitation constant, initial density, and ratio of specific heats, whereas the weight from which molecules moving with velocity C just fail to escape is given by

$$M = \frac{3}{4\pi} \frac{C^3}{\gamma^{\frac{3}{2}}\rho^{\frac{1}{2}}}.$$

With $\kappa = 1\tfrac{2}{3}$ the minimum weight of condensation is 9·7 times the weight which is just adequate to retain the molecules.

however slight, causes it to change its configuration entirely; it had the dynamical attributes of a stick balanced on its point, or of a soap-bubble which is just ready to burst.

PRIMAEVAL CHAOS. These general theoretical results may now be applied to any mass of gas we please. Let us begin by applying them to Newton's hypothetical "matter evenly disposed throughout an infinite space." We return in imagination to a time when all the substance of the present stars and nebulae was spread uniformly throughout space; in brief, we start from the primaeval chaos from which most scientific theories of cosmogony have started.

We have already seen that if all the substance of the present universe—nebulae, stars, stray matter and everything else—were uniformly scattered through space, there would be something like 10^{-30} gramme of matter to the cubic centimetre, so that this is the kind of density we must assign to the hypothetical primaeval nebula. It is almost inconceivably low. In ordinary air, at a density of one eight-hundredth that of water, the average distance between adjoining molecules is about an eight-millionth part of an inch; in the primaeval gas we are now considering, the corresponding distance is about four yards. If the amount of air which occupies the space of a pinhead in our atmosphere were reduced to this density, it would occupy a thousand million cubic miles—a cube a thousand miles each way. The contrast again leads back to the theme of the extreme emptiness of space.

We must, however, not forget that the universe appears to be expanding very rapidly, and changing its mean density of matter in space. The mean density of the primaeval chaos may have been greater or less than now according as space has increased or decreased its volume in the meantime. Possibly also we ought to increase the density to allow for matter which existed

in the primaeval chaos but has since turned into radiation. Assuming the Friedmann-Lemaître cosmology Eddington has estimated that the mean density of matter in the original Einstein space must have been about 10^{-27} just mentioned, a thousand times as great as that we have estimated for the present universe.

We proceed to inquire what is the minimum weight of condensation that would persist in a primaeval gas of such density..

Calculation shews that if ordinary air were attenuated to a density of 10^{-30}, so that its molecules were four yards apart, no condensation could persist and continue to grow unless it had at least ten million times the weight of the sun; any smaller weight of gas would exert so slight a gravitational pull on its outermost molecules, that their normal molecular speeds of 500 yards a second would lead to the prompt dissipation of the whole condensation.

Hence if such a gas were spread uniformly in space, and disturbed in any way, all incipient condensations whose mass was less than that of ten million suns would be smoothed out, and the gas would ultimately break up in larger condensations each having ten million times the mass of the sun or more.

We can carry out similar calculations with reference to other assumed molecular velocities. The following table shews the weights of condensations which would be formed in primaeval masses of chaotic gas of this same density 10^{-30}, with the molecules moving at different speeds:

Molecular speed	Minimum weight (in terms of sun's mass)
500 yards a second	10,000,000
2,000 " " "	640,000,000
10,000 " " "	10,000,000,000

If we make similar calculations for a density of 10^{-27} gramme per cubic centimetre, the masses prove to be only a thirty-second part of those tabulated above; with the smaller density of 10^{-33}, the masses are thirty-two times those tabulated.

All known stars have weights comparable with that of the sun. Thus if, as Newton conjectured, the stars first came into being as condensations of this kind, then the entries in this table ought to be comparable with unity. Newton's conjecture, in the form in which we have just considered it, is clearly untenable, since all the calculated weights are many millions of times that of the sun. If there ever existed a primaeval chaos of the kind we are now considering, it would not condense into stars, but into enormously more massive condensations, each having the weight of millions of stars.

THE BIRTH OF THE GREAT NEBULAE

Now it is significant that bodies are known in space having weights equal to those just calculated, namely the great extra-galactic nebulae. We have already seen (p. 79) that there are two nebulae whose weights can be determined with fair accuracy, namely the Great Nebula in Andromeda (Plate VII, p. 32) and the nebula N.G.C. 4594 in Virgo (Plate XXI, p. 230). Hubble estimates the weights of these to be 3500 million and 2000 million times the weight of the sun respectively.

Thus it is to the great nebulae and not to the stars that we must look for masses comparable with those just tabulated. The general magnitude of nebular masses is such as to suggest that the condensations which would first be formed out of the primaeval nebula must have been the great extra-galactic nebulae, and not mere stars. It is of course at best only a conjecture that the great nebulae were formed in this manner—if for no other reason because we can never

know whether the hypothetical primaeval nebula even existed—but it seems the most reasonable hypothesis we can frame to explain the fact that the present nebulae exist. These nebulae are so generally similar to one another that it seems likely that they must all have been produced by the action of the same agency, and that which we have just considered provides a reasonable explanation which, apart from the postulated existence of the continuous primaeval nebula, is based on *verae causae*.

We may notice that if the nebulae came into being in this way, the molecules must have moved with very high speeds—possibly of the order of 10,000 yards a second, or more than 20 times the molecular speed of ordinary air. The molecules of ordinary air can never attain such speeds as this. Their speeds increase as the temperature of the air increases, but not indefinitely; the heat breaks the molecules up into their atoms before they reach speeds of 10,000 yards a second. Again the heat breaks up the atoms before their speeds reach 10,000 yards a second; it sets free a few of the outermost electrons.

If, then, we imagine the nebulae to have formed as condensations in a primaeval chaos, this chaos cannot have consisted of complete molecules nor even of complete atoms. It must have consisted of a mixture of loose electrons and atoms with possibly a few complete molecules. Starting from such a primaeval chaos, it is quite easy to suppose the nebulae to have formed as gravitational condensations, precisely as imagined by Newton. The temperature of the primaeval matter need not have been very high. Even at ordinary room temperatures, free electrons move at an average speed of 120,000 yards a second, so that the presence of even a few free electrons raises the average speed of a mixture very substantially.

The great nebulae are of course not all exactly similar to one another, and our next inquiry must be as to the origin of their differences.

If the condensations in the primaeval gaseous nebula had formed and contracted in an absolutely regular fashion, the final product would be an array of perfectly equal and similar masses of gas spaced with perfect regularity. But we seldom find nature behaving with such perfect regularity as this; and we need not be surprised that the observed nebular array is not evenly spaced, or that its members are neither equal in weight, nor symmetrically arranged. As the original condensations in the primaeval gas contracted, they must have produced currents, and these would hardly be likely to occur absolutely symmetrically. If the motion in each mass of condensing gas had been directly towards the centre of the condensation at every point, the final result would have been a spherical nebula devoid of all motion, but any less symmetrical system of currents would result in a spin being given to each contracting mass. This spin would no doubt be very slow at first, but the well-known principle of "conservation of angular momentum" requires that, as a spinning body contracts, its rate of spin must increase. Thus, when the process of condensation was complete, the final product would be a series of nebulae rotating at different rates.

NEBULAR ROTATION. And this is exactly what is observed; so far as our evidence goes the nebulae are in rotation, and at different rates. The various parts of the surface of any rotating mass necessarily have different speeds in space. The sun for instance rotates about its axis in such a direction that the surface we see is moving always from east to west; as a result the eastern limb is always advancing towards the earth, while the western limb is receding from us. A spectro-

scope turned on to different parts of the sun's surface in succession at once reveals these differences of speed; they not only assure us of the sun's rotation, but enable us to measure its amount. The nebulae may be examined in the same way, and the examination shews that a large number of them are rotating with the perfectly regular motion of a solid body—a spinning-top, for instance. Measured by terrestrial standards their rates of rotation seem extraordinarily slow; for instance the Great Nebula *M* 31 in Andromeda requires about 19,000,000 years to make a complete rotation, but this apparent slowness is an inevitable result of the huge size of the nebula. Even to get round once in 19,000,000 years, the outer parts of the nebula have to move with speeds of hundreds of miles a second.

A few of the nebulae are quite irregular in shape, but the majority have regular shapes, and it is highly significant that these are precisely the shapes which, it can be calculated mathematically, would be exhibited by rotating masses of gas. Actually there is a far stronger case than this for supposing the nebulae to be rotating masses of gas. From the purely observational evidence of surface-brightness and other characteristics, Hubble found that nearly all of these nebulae could be arranged in a single linear sequence—they could be arranged in order like beads on a string. And this order proved to be practically identical with the sequence which had previously been calculated, by purely theoretical methods, for the configurations of masses of gas rotating at gradually increasing rates of speed.

Let us examine this sequence of theoretical configurations in their natural order.

A mass of gas which was not rotating at all would of course assume a spherical shape under its own gravi-

PLATE XX

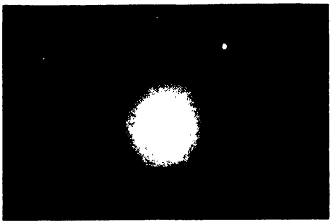


Fig. 1
N.G.C. 3379

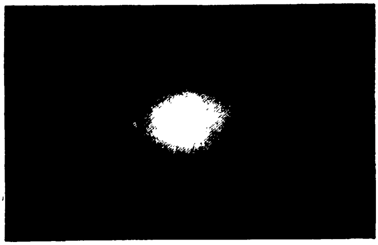


Fig. 2
N.G.C. 4621

Fig. 3
N.G.C. 3115

Fig. 4
N.G.C. 4594
in Virgo

tation. A number of perfectly spherical nebulae are known; a typical example is shewn in fig. 1 on Plate XX.

With slight rotation the mass assumes the shape of a slightly flattened orange, like the earth or Jupiter. Nebulae of this shape are also known in abundance; an example is shewn in fig. 2 on the same plate.

With a higher degree of rotation the degree of flattening increases, but theoretical calculation shews that the orange shape is soon departed from. The equator first begins to shew a pronounced bulge, until finally, with sufficient rotation, this develops into a sharp edge, the rotating mass now being shaped like a double-convex lens. This prediction of theory is abundantly confirmed by observation, a large number of these lens-shaped nebulae being observed in the sky. An example is shewn in fig. 3 on Plate XX.

The next step is somewhat sensational. Further rotation does not, as might be expected, result in still further flattening. Up to now, each increase in rotation has increased the sharpness of the equatorial bulge, but this is now as sharp as it can be. Theory shews that the flattening has also proceeded to the utmost possible limit, and that the next stage must consist in matter being ejected through the sharp edge of the equator and spread throughout the equatorial plane. Here again observation confirms theory; figs. 4 and 5 (Plate XX) shew types of nebulae actually observed, the former being the nebula in Virgo which we have already had under discussion.

The comparatively thin layer of gas which now lies in the equatorial plane is similar in one respect at least to the matter "evenly disposed throughout an infinite space" from which Newton imagined the stars to be born. Disturbances can be set up in it in a variety of ways, and any disturbance, no matter how slight, must

result in the creation of a series of condensations. As before, those below a certain limit of size disappear of themselves, while those above this limit continually increase in intensity until they have absorbed all the gas in the equatorial plane. Again, as with the hypothetical primaeval chaos, we can calculate the minimum size of condensation which can be expected to have a permanent existence, and once again the result proves to be highly significant.

Hubble's estimates of the total weights of two conspicuous nebulae have already been given. As the distances, and therefore also the sizes, of both these nebulae are known, it is an easy matter to calculate the average density of the gas throughout the whole nebula. In each case the average density is found to be of the order of 10^{-21} gramme to the cubic centimetre, so that, it is natural to suppose that the average density of gas in all the nebulae must be of this order.

On proceeding to calculate the weights of the smallest condensations which could form and persist in a gas of this low density, we obtain the results shewn in the following table. The molecular velocities are taken rather low, so as to allow for the cooling which must occur when the gas is spread out in the equatorial plane of the nebula.

Molecular speed	Weight of condensation in terms of Sun
100 yards a second	2·5
300 ,, ,,	65
500 ,, ,,	330
1000 ,, ,,	2500

Again the weights of the condensations are given in terms of the weight of the sun. And the significant fact emerges that most of the entries in the table represent weights comparable with that of the sun. We are

dealing with stellar weights at last; the condensations which must form in the outer regions of the great nebulae will have weights comparable with those of the stars.

THE BIRTH OF STARS

And indeed it seems reasonable to conjecture that the process we have just been considering is that of the birth of stars. Even a casual glance at photographs of nebulae suffices to shew that the matter which has been ejected into the equatorial plane of a nebula does not lie uniformly spread out in that plane; it is seen to have fallen into bunches, knots or condensations. These are apparent enough in many of the nebular photographs already shewn, but they can be seen still more clearly in nebulae which are viewed nearly full on, such as for instance the striking nebulae shewn in the lower half of Plate XXI (p. 230), and in Plates XXII and XXIII.

These bunches are invariably too large to be interpreted as single stars; they are more probably groups of stars. In the largest telescopes they break up into great numbers of points of light in the way already exhibited in Plate XIV (p. 77). We have already mentioned the reasons which compel us to regard these points of light as actual stars, the principal being that some of them shew the characteristic light-fluctuations of the Cepheid variables. It is not altogether clear whether the stars are formed directly as condensations in the equatorial plane of the nebula, or whether larger condensations form first, namely the bunches, observable in nebular photographs, which subsequently form smaller condensations, the stars. On the whole it seems likely that there are two processes involved—first the break-up of the nebular matter into big condensations, and then the break-up of these big condensations into stars. Such a succession of processes might well accom-

pany a gradual cooling of the matter, and it is of course possible that there are even more than two processes involved. There is no need to form a final opinion on this at present, as it is in no way essential to the progress of the main argument.

A collection of nebular photographs enables us to follow nebular evolution from the earliest stages shewn in Plate XX (p. 227), through the first formation of the equatorial ring of matter, and the appearance of granular bunches, such as are shewn in Plates XXI and XXII, and the first distinct appearance of stars shewn in Plate XXIII, down to the later stages, such as are shewn in Plates XXIV and XXV, in which the nebula appears to be but little more than a cloud of stars. Hubble has found it possible to follow the sequence still farther, and can trace a continuous transition from the nebulae of this last type to pure star-clouds such as the Greater and Lesser Magellanic Clouds shewn in Plate XXVI.

Thus the stars appear to have been born in much the same way as we have conjectured that their parents, the great nebulae, had been born before them, namely, through the agency of what is generally known as "Gravitational Instability." This causes any mass of chaotic gas to break up into detached condensations, and, the more tenuous the original gas, the greater the weights of the condensations formed out of it. The original primaeval nebula was of such low density that the condensations which formed in it weighed thousands of millions of times as much as the sun. These increased their density so much in contracting that when their rotation caused them to eject gaseous matter, this condensed into masses of stellar weight which we believe actually to be stars.

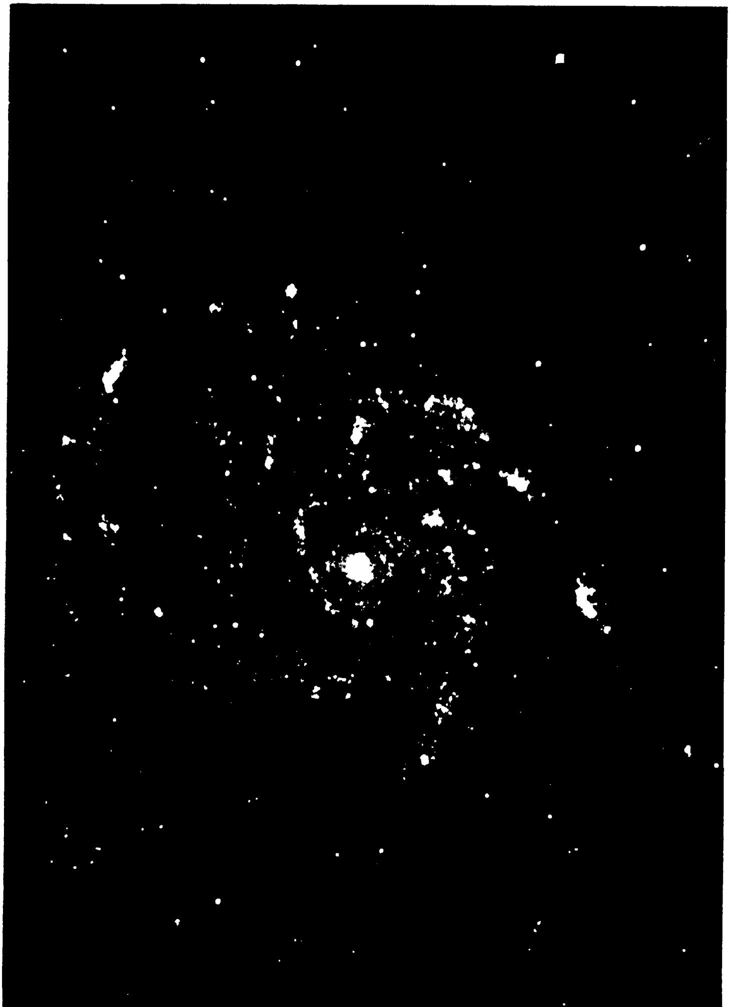
We have less certain knowledge of the former process than of the latter. Our only reason for thinking that the former process ever occurred at all is that the extra-

The Nebula N.G.C. 4594 in Virgo

Mt Wilson Observatory

The Nebula N.G.C. 7217

PLATE XXIV



Mt Wilson Observatory

The Nebula *M* 101 in Ursa Major

galactic nebulae now exist; there is no evidence that the primaeval chaotic nebula ever existed, beyond the fact that the hypothesis of its previous existence leads to a very satisfactory explanation of the present nebulae existing as they now do. On the other hand, we not only know that the stars exist: we also know that the masses of gas exist out of which theory shews that stars must necessarily be born. They are the tenuous equatorial fringes of the great nebulae. Our telescopes shew us both the nebular fringes and the stars, and we can almost study the actual process of birth.

THE GALACTIC SYSTEM OF STARS. If this is the true account of the birth of the stars, then our sun and its companions in space must have been born out of a rotating nebula. Observation gives strong support to this conclusion. Since the time of the Herschels, it has been a matter of frequent comment that the galactic system has the general shape of the extra-galactic nebulae, the galactic plane of course representing the equatorial plane of the original nebula. On purely observational grounds, present-day astronomical thought is moving rapidly towards regarding the whole galactic system either as a rotating nebula or the remains of one.

Each star in this system moves in a complicated orbit under the gravitational attraction of all the other stars of the system. It is not possible to calculate this orbit in detail. The orbit of a planet round the sun is easily calculated because only two bodies are involved, the planet and the sun. But even when there are only three bodies involved, it is impossible to calculate the orbits that each describes under the attractions of the other two jointly: this is the famous problem of three bodies, which has never been solved. When, as in the galactic system, thousands of millions of stars are involved, it is naturally useless to try to calculate the

orbit of each star—it would be as futile as trying to calculate the path of each molecule in a gas.

Yet the same statistical methods which give us useful information as to the properties of a gas may be applied to studying the motions of the stars. There are so many stars that we do not trouble about individuals at all, we just treat them all together as a crowd. To treat them as individuals would be as though the railway company tried to forecast the Bank Holiday traffic from London to Brighton by considering the finances, habits and psychology of each individual Londoner.

Without going into individual details, we can see that each star must describe an orbit which, after touring round a large part of the galaxy, comes back to somewhere near its starting point. Calculation shews that each such circuit must take hundreds of millions of years to complete. Even so, the stars will mostly have performed several complete circuits while the earth has been in existence, and if we are right in supposing the stars to be far older than the earth, each star may have toured round the galaxy several thousands of times. We should accordingly expect the galaxy to have assumed a definite permanent shape by now; the distribution of stars in its different parts ought to have become something like steady, and the stars ought to have settled down to a state approximating to one of steady motion.

Statistical methods of investigation shew that there is not a great number of possible arrangements for a system of stars which has lived long enough to attain a steady state. If the system as a whole has no rotation at all, there is only one arrangement; the stars form a globular mass with perfect symmetry in all directions. The observed globular clusters (Plate XII, p. 69) provide good approximations to this type of formation, although

Shapley has found that the majority are not absolutely spherical in shape. If the system as a whole is endowed with rotation, the possible configurations are all of a flattened symmetrical shape, like a coin, a watch or a round biscuit—in other words a system of stars in rotation must be shaped pretty much as we believe the galaxy to be shaped.

Thus the shape of the galactic system suggests that the system must be in a state of rotation. And, as we have seen (p. 74), recent observational researches by Oort, Plaskett and others make it fairly certain that the rotation required by theory is an actual fact. The motions of the stars indicate that the whole galactic system is rotating at a rate which varies from one region to another, being about one revolution every 250 million years in the vicinity of the sun.

Moreover, since rotation cannot be generated out of nothing, we must conclude that the galactic system must have been born out of a rotating body. We are acquainted with only one type of astronomical body which is of sufficient size to turn into a galactic system, namely the great nebulae, and as the majority of these are believed, and some are known with certainty, to be in rotation, it seems reasonable to conclude that the galactic system must have been born out of a nebula, unless indeed its structure is still such that we should even now describe it as a nebula if we saw it from the great distance from which we view the other great nebulae. The observed period of rotation of the galactic system, of the order of 250 million years, is substantially longer than the period, either known or suspected, of any of the nebulae, but the dimensions of the galactic system are also greater than those of any known nebula, and the two facts hang together. Again, the number of stars in the galactic system is probably substantially higher than in any nebula, as also is the total weight of

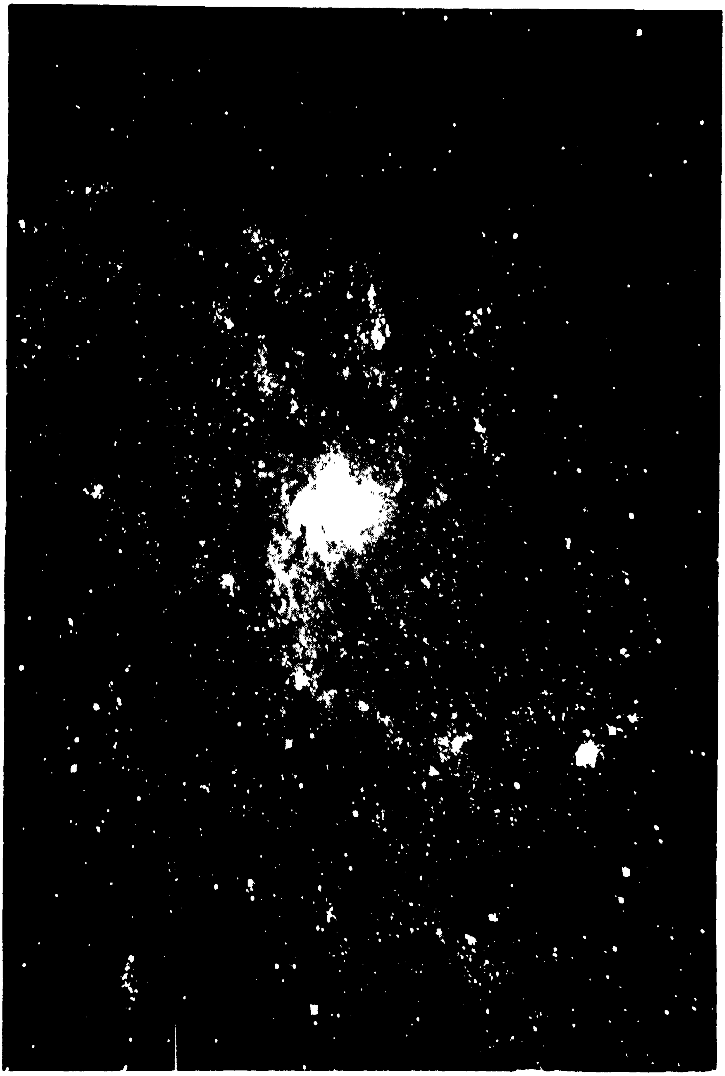
these stars*. All this makes it clear that if the galaxy is, or ever has been, one of the great nebulae, it must have been one of unusual size and weight.

We have seen how the sun and all the stars are continually losing weight as the result of their emission of radiation. It follows that the total weight of the galactic system is for ever decreasing, and as a consequence its gravitational hold on its constituent stars is continually weakening. If this gravitational hold were suddenly to vanish altogether, each star would replace its present curved path by a perfectly straight line, along which it would travel at its present speed undeflected by any gravitational forces from other stars, so that the stars which now constitute the galactic system would soon be scattered through the whole of space. In brief, if the gravitational pull of the stars were suddenly abolished, the galaxy would begin to expand at a great rate.

Although this is not likely to happen, the gradual abolition of the gravitational pull of the stars, as they turn their weight into radiation, must cause the galaxy to expand all the time, although only at an exceedingly slow rate: calculation suggests that its present rate of expansion would double its size in about 30 million million years. If, however, the stars are of the great ages we are inclined tentatively to assign to them this rate of expansion may have been more rapid in the past, when the stars were full of youthful vigour and squandered their substance more lavishly than now, so that it seems probable that the galactic system was substantially smaller and more compact in the past and the original nebula probably smaller still.

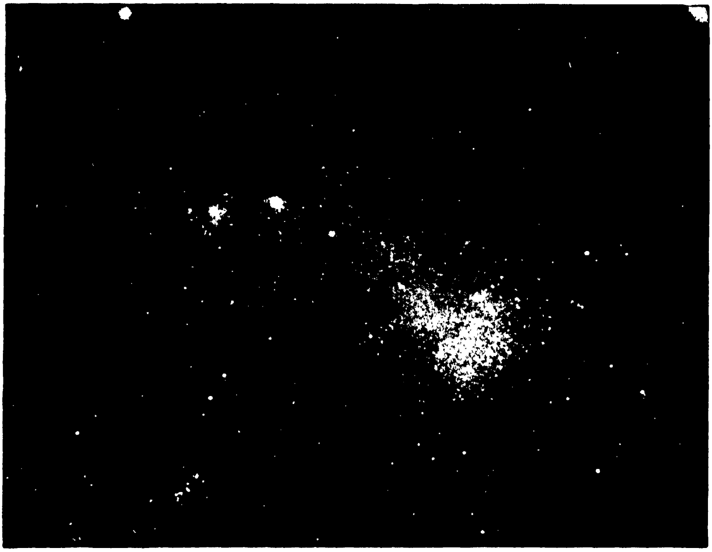
* The following estimates have already been mentioned:

Weight of Galaxy in terms of sun	110,000,000,000
„ nebula *M* 31 in terms of sun	3,500,000,000
„ „ N.G.C. 4594 in terms of sun	2,000,000,000



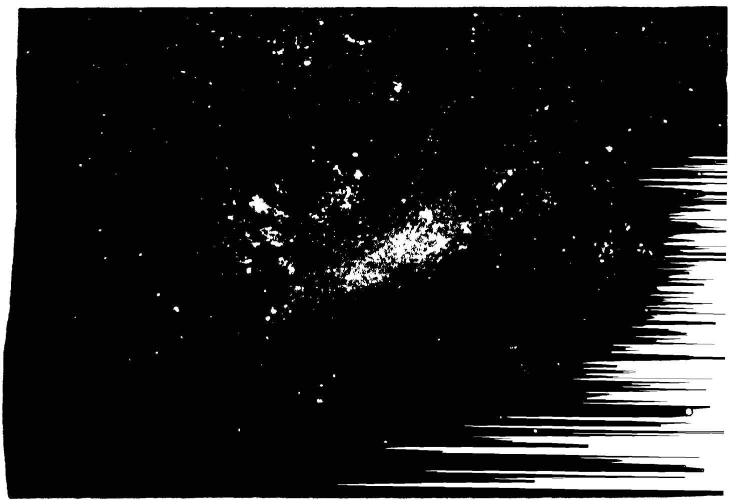
Mt Wilson Observatory

The Nebula *M* 33 in Triangulum



Harvard (Arequipa) Observatory

The Lesser Magellanic Cloud



Franklin-Adams Chart

The Greater Magellanic Cloud

STAR CLUSTERS. We have seen how the stars in the great nebulae appear to be congregated in bunches or clusters. The globular clusters in the galactic system (p. 229) may possibly be similar bunches of stars, which have remained undisturbed by other groups of stars and so have assumed the globular form under their own attraction—just as a mass of gas would do. Shapley finds that these clusters lie somewhat outside the galactic plane; it looks as though they were broken up or disorganised in travelling through this plane, where they would encounter other stars.

By contrast, the groups of stars of the type generally described as moving clusters (p. 191)—the Pleiades, the Hyades, the stars of the Great Bear and a crowd of others voyaging in company with them through space—are generally found to move in the galactic plane. These may quite possibly represent the final vestiges of globular clusters which have been broken up by interaction with other stars, all except the most massive members having been knocked out of formation. As already mentioned, mathematical analysis shews that the interaction between the stars of such moving clusters and other stars in the galactic plane would cause each cluster to assume the shape of a flat biscuit or watch, of diameter equal to 2½ times its thickness. It is significant that the majority of the moving clusters shew a flattening of this kind, its amount agreeing tolerably well with the calculated value. It is even conceivable that the "local cluster" surrounding the sun (p. 72) may be the remains of such a bunch of stars.

The motions of these clusters may also induce a further flattening, in a direction perpendicular to their motion. Some clusters shew this further flattening, the Ursa Major cluster being a striking example.

THE BIRTH OF BINARY SYSTEMS

In discussing the way in which nebulae might be born out of chaos, we noticed that the existence of currents in the primordial medium would endow the resulting nebulae with varying amounts of rotation. For the same reason the children of the nebulae, the stars, must also be endowed with rotation at their birth. There is a further reason for such rotation. The general principle of the "conservation of angular momentum" requires that rotation, like energy, cannot entirely disappear. Its total amount is conserved, so that when a nebula breaks up into stars, the original rotation of the nebula must be conserved in the rotations of the stars. Thus the stars, as soon as they come into being, are endowed with rotations transmitted to them by their parent nebula, in addition to the rotations resulting from the currents set up in the process of condensation.

Their continual radiation of energy causes the physical conditions of the stars to change, and we shall find in the next chapter that this change generally involves a shrinkage of the star's diameter. The same principle of "conservation of angular momentum" now requires that, as a star shrinks, its speed of rotation shall increase. In brief, as a star ages, it spins faster and faster.

We have already seen (p. 57) how the rotations of stars can now be detected and measured by spectroscopic methods. The method has so far been confined mainly to the largest stars, and here the law just mentioned appears to be confirmed. The largest stars of all—the "red giants" described on p. 298—shew little or no evidence of rotation, while the blue stars of substantially smaller size shew rapid rotation, their velocities ranging up to 200 miles a second and more

at their equators. While this is satisfactory so far as it goes, we must remember that spectroscopic observation merely discloses the speed of rotation of a star's outer surface; it tells us nothing of the rotation of the inner layers. A star does not rotate uniformly like a rigid body, as is sufficiently shewn by the fact that the sun's atmosphere has different periods of rotation in different latitudes. And it can be shewn theoretically that long-continued radiation from a star exercises a braking effect on the outermost layers of the star, so that after a sufficient time the outer layers of the star may be rotating far more slowly than the inner layers.

Now rotation was the essential factor in the birth of the stars out of the parent nebula. A nebula perfectly devoid of rotation would not, so far as we can see, break up into stars at all, and this prediction of theory appears to be confirmed by observation, since nebulae of the perfectly spherical type shewn in fig. 1 of Plate XX are never resolved into stars in the telescope. On the other hand, we saw how nebulae which were initially endowed with rotation would continually increase their speed of rotation under shrinkage, until finally their rotation broke them up and produced a family of stars out of each. The question now obviously arises whether, as the speed of rotation of the stars increases, these are likely to break up in their turn, and produce yet a third generation of astronomical bodies. Again we might expect that mathematical analysis would apply to large and small bodies equally, irrespective of scale. And a detailed examination of the problem shews that in actual fact the process we have had under consideration would repeat itself, and again bring a further generation of smaller bodies into being, provided the physical conditions were suitable.

The physical conditions, however, prove not to be

suitable; they certainly fail in one respect at least. Although a rotating star may eject gaseous matter in its equatorial plane, the whole process will be on a much smaller scale than in the nebulae. We might expect the ejected matter to form condensations as before, but calculation shews that, unless the molecular velocity is extraordinarily low, no condensation can survive unless it has a weight greater than the whole weight of the star! This means that with any reasonable molecular velocity, the ejected gas would not form condensations at all. It would merely scatter into the surrounding space, forming an atmosphere without any distinct condensations.

Such is the course of events if the stars, like the nebulae before them, are treated as pure masses of gas. Another alternative must, however, be considered.

THE FISSION OF LIQUID STARS. We have seen how a gaseous nebula devoid of rotation would assume a strictly spherical shape under its own gravitational attraction, while slight rotation would cause it to flatten into an orange shape, like the earth. The earth also has assumed this shape on account of its rotation, although its internal structure is very different from that of a gaseous nebula.

Strict mathematical investigation shews that this flattened-orange shape must be common to all slowly rotating bodies, regardless of their internal composition; gases, liquids and plastic bodies assume it equally. But the shape of a body which is rotating more rapidly must depend very greatly on its internal arrangement and constitution, being especially affected by the extent to which the weight of the body is concentrated near its centre.

As a consequence of the high compressibility of gases, this central concentration of weight reaches its extreme limit in a purely gaseous mass. The opposite

extreme is reached in a mass of uniform incompressible liquid such as water, in which there can be no central concentration at all. As a mass of this latter type increases its speed of rotation, the slightly flattened-orange shape merely gives place to the shape of a more flattened orange. The tendency of a gaseous mass to form a sharp edge round the equator is entirely absent, and the cross-section of its figure remains elliptical throughout. At a still higher speed of rotation the equator loses its circular shape and it too becomes elliptical. The figure has now three unequal diameters, but every cross-section is strictly elliptical; the figure is an "ellipsoid." After this, its longest diameter begins to elongate until the mass, still ellipsoidal in shape, has formed a cigar-shaped figure with a length nearly three times its shortest diameter.

A new series of events now begins. The mass of liquid gradually concentrates about two distinct points on its longest diameter, a waist or furrow forming across its middle. This furrow becomes deeper and deeper until it has cut the body into two distinct detached masses, which now rotate in orbital motion about one another and form a binary star. The sequence of events is shewn in fig. 10; diagrams of the final stage as represented by actual binary stars have already been given on p. 60.

For comparison the sequence of shapes assumed by a rotating mass of gas is shewn in fig. 11, this being identical with the sequence of observed nebular shapes which is actually observed, and is illustrated photographically in Plate XX (p. 227).

The two chains of configurations shewn in figs. 10 and 11 represent, it will be remembered, the two extreme cases of a rotating body whose substance is distributed with complete uniformity, and of a rotating body whose substance is very highly condensed towards its centre.

As the constitutions of actual astronomical bodies must lie somewhere between these two extremes, we might naturally expect such a body to follow a series of configurations intermediate between the two shewn in

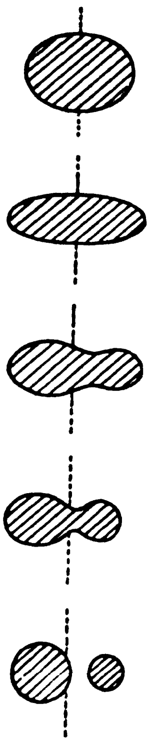


Fig. 10. The sequence of configurations of a rotating mass of liquid.

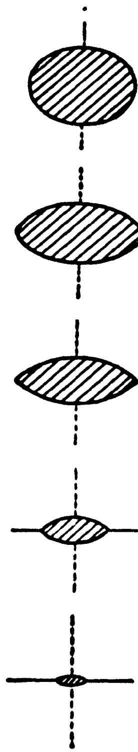


Fig. 11. The sequence of configurations of a rotating mass of gas.

figs. 10 and 11. Theory shews that as a matter of fact it does not. All bodies having less than a certain critical degree of central condensation follow the sequence shewn in fig. 10, or a sequence differing only immaterially from this; all bodies having more than

this critical amount of central condensation follow the sequence shewn in fig. 11. Thus, when this critical degree of central condensation is reached there is a sudden swing over from fig. 10 to fig. 11. In brief, every rotating body conducts itself either as if it were purely liquid, or as if it were purely gaseous; there are no intermediate possibilities.

Observational astronomy seems to suggest that a great number of stars, possibly even all stars, follow the sequence shewn in fig. 10. No other mechanism, so far as we know, is available for the formation of the numerous spectroscopic binary systems, in which two constituents describe small orbits about one another. In these stars, then, the central condensation of mass must be below the critical amount just mentioned; to this extent they behave like liquids rather than gases.

THE DEVELOPMENT OF BINARY SYSTEMS

TIDAL EFFECTS. The moon exerts gravitational forces on the earth and these produce the tides in our oceans. The nearness of the moon is an essential feature in the production of these tides. A very distant moon would exert a gravitational pull which would be uniformly the same at all parts of the earth. With the moon reasonably near to the earth, the pull on those parts of the ocean which are nearest to, and so directly under the moon, is substantially greater than the average pull exerted on the solid earth as a whole, while the pull on the antipodally opposite parts of the ocean—those farthest away from the moon—is substantially less. If the earth was not rotating, the difference in these pulls would cause the water to be exceptionally near to the moon at the former point, and exceptionally far from it at the latter. In other words there would be

two points of high tide, one just under the moon and one antipodally opposite. The combination of this effect and the earth's rotation produces the complicated phenomenon of our ocean tides.

TIDAL FRICTION. When a rotating astronomical mass first breaks up to form a binary system, the two components are so near that they necessarily raise tremendous tides in one another. They may no longer be treated as rigid bodies, so that their gravitational attraction no longer causes them to move in simple circular elliptical orbits. On the contrary, their tides complicate the gravitational pulls between the two bodies enormously, and produce a new series of effects which Sir George Darwin studied under the name of "Tidal Friction." He shewed that the new forces set up by the tides must drive the two bodies apart, and equalise their rates of rotation in so doing. After these processes have been in operation for millions of years, the rates of rotation of the two bodies and their rate of revolution about one another must all become equal, so that each body perpetually turns the same face to its companion, and the two rotate about one another like the two masses of a dumb-bell joined by an invisible arm.

Although a sun and planet do not form a binary system in the strict technical sense, they are necessarily subject to the same forces as true binary systems. Thus we can see the operation of tidal friction in the fact that Mercury always turns the same face to the sun, and that Venus rotates so slowly on its axis that it turns the same face to the sun certainly day after day, probably also week after week, and possibly even for all time. As we pass farther out into space the effects of tidal friction rapidly diminish, but it is probably significant that the nearer planets, Earth and Mars, have days of about 24 hours each, while the

remote planets Jupiter, Saturn and Uranus each have days of only about 10 hours. The periods of rotation of Neptune and Pluto are unknown. Apart from these we find, in a general way, that the farther we recede from the sun the more rapidly the planets rotate, which is precisely the effect that ought to be produced by tidal friction.

In the same way, tidal friction has in all probability been mainly responsible for the present configuration of the earth-moon system, driving the moon away to its present distance from the earth and causing it always to turn the same face towards us. Tidal friction must of course still be in operation. As the moon raises tides in the oceans of the earth, these exert a pull on the solid earth underneath, and so slow down its speed of rotation, with the result that the day is continually lengthening, and will continue to do so until the earth and moon are rotating and revolving in complete unison. When, if ever, that time arrives, the earth will continually turn the same face to the moon, so that the inhabitants of one of the hemispheres of the earth will never see the moon at all, while the other side will be lighted by it every night. By this time the length of the day and the month will be identical, each being equal to about 47 of our present days.

After this, tidal friction will no longer operate in the sense of driving the moon farther away from the earth. The joint effect of solar and lunar tides will be to slow down the earth's rotation still further, the moon at the same time gradually lessening its distance from the earth, until finally it meets the fate we shall describe below (p. 271).

Jeffreys has made a study of the length of time needed for all these processes to occur. As has been already mentioned (p. 174), he estimates that it must have required something like 4000 million years for

the earth-moon system to reach its present configuration; he has further estimated that about another 50,000 million years will be required before day and month become identical in length, so that the earth always turns the same face to the moon.

Similar events must of course take place in a true binary system—a double star which has resulted from the excessive rotation of a single body. Tidal friction will at first cause the two components of a binary system to move apart from one another, but after they have receded to a certain distance, it will tend to bring them together again. The components of the true binary star attain a configuration like that of the earth-moon system in a brief fraction of their lives, and, passing on, reach in time the configuration in which each perpetually turns the same face to the other. Up to now, tidal friction has been driving the masses ever farther apart, but as soon as this stage is attained, the tides become stationary on both components, so that tidal friction goes out of operation. Thus the separation produced by tidal friction has now reached its limit, and, so far as tidal friction is concerned, the two bodies might rotate in the way just described to all eternity; their superfluous energy of rotation has all been expended in dragging them apart in opposition to the gravitational pull between them, and there is no energy available to drag them farther apart.

This maximum distance of separation can be calculated, and for an average binary star it proves to be only a very few times the diameter of either constituent. In most binary systems, the distance between the two constituents is far greater than can be accounted for by the operation of tidal friction alone, so that either some other agency has been at work separating the two bodies, or else the two bodies did not come into being through the fission of a single star.

Broadly speaking, binary systems may be divided into the two classes of spectroscopic binaries (see p. 58) and visual binaries (see p. 42). To all appearances the spectroscopic binaries form a single continuous sequence, starting with systems in which the two components are almost in contact and are describing orbits which are either perfectly circular or are very nearly so. It is reasonable to suppose that these have just broken up by fission, so that the remainder of the sequence probably pictures the further development of systems which have been formed by fission.

As we proceed along the sequence, the distance between the two constituents continually increases, until it becomes much greater than the maximum separation which tidal friction could produce. Some other agency, then, must have been at work separating the two bodies.

The essential factor in the problem is that to separate two bodies against their mutual gravitational pull involves the expenditure of a great amount of energy—it is like raising a heavy weight from the surface of the earth. Thus, whatever agency has been at work separating the two bodies it must have provided a large amount of energy. It is readily shewn that a general expansion of the universe (see p. 91) would provide what is effectually a large store of energy, but it can also be shewn that the two components of a binary system would not share in this general expansion, their gravitational pull almost entirely neutralising the tendency to expansion. Consequently, this store of energy is not available.

LOSS OF WEIGHT. Our thoughts turn to the stores of energy from which the stars discharge their radiation, and we find that as tidal friction becomes inoperative, this provides the energy for effecting a further separation of the two constituents of a binary star.

A simple analogy will shew the mode of operation. The earth is at its present distance from the sun because this distance is exactly suited to the present weight of the sun. If the sun's weight were suddenly reduced to half, its gravitational pull on the earth would also be reduced to half, and the earth would move to a greater distance from the sun*.

The sun's weight is not likely to be suddenly reduced to half, but it has been reduced by a thousand million tons in the last four minutes, with the result that its gravitational grip on the earth has been weakened and the earth has moved out to a wider orbit; at this moment the radius of the earth's orbit is greater than it was four minutes ago. The details can be traced out mathematically with complete precision. It appears that the earth's orbit round the sun is not a circle, nor even an ellipse of small eccentricity; it is a spiral curve, like an uncoiled watch spring. Every year the earth moves a tiny step farther out into the outer cold and darkness; exact calculation shews that its average distance from the sun increases at the rate of about a metre (39·37 inches) a century. The effect is of course of precisely the same kind as we have seen must be produced in the galactic system by the loss of weight of the stars. The only difference is that in the galaxy a system of thousands of millions of stars is expanding, whereas the sun-earth system consists of only two members.

Precisely similar effects must be produced by the loss of weight in the two components of a binary star. Here both components are radiating away energy, and so are simultaneously losing weight. Detailed calculation shews that they must continually recede from one

* Although the details are unimportant, the actual course of events would be that the earth would begin to describe an elliptic instead of a circular orbit about the sun, the earth's *average* distance being greater than now.

another, but that the shape of their orbit will undergo no change.

Yet neither separately nor in combination can the two effects just described explain either the shapes or the sizes of the observed orbits of binary stars as a whole. To interpret these we must find yet a further store of energy. Now the only other known store of energy is that derived from the motion of other stars. Now and then, although only at very infrequent intervals, other stars must pass so near that their gravitational influence becomes appreciable. They then exert different gravitational pulls on the two components of the binary system in the way already described (p. 186) and so change both the dimensions and shape of its orbit. It would be an impossible task to try and trace out the changes in any single system, but again we can use statistical methods and again we can shorten the discussion by making use of knowledge which has already been obtained in the analogous problem over the motion of the molecules of a gas. We have already seen how these account for the statistical distribution of orbits which is actually observed.

Although many of the details are still uncertain, and there are still many difficulties in the problem, it seems likely that the combination of all three agencies, tidal friction, extending over millions of years, loss of weight, extending over millions of millions of years, and disturbance from passing stars, extending over a similar period, will ultimately prove capable of explaining the evolution of binary star systems. Their aggregate effect is to widen the distance between the two stars, while at the same time knocking the orbit out of shape.

SUBDIVISION. While these changes are going on in the orbital arrangement of a binary system, the two components are themselves changing their physical condition on account of their continual loss of weight,

primarily on theoretical grounds alone, but observation confirms it at almost every step. Indeed, the evolutionary sequence could have been discovered almost equally well from observational evidence alone, except for the hypothetical primaeval chaos, about which, from the nature of the case, observation cannot have anything to say.

THE ORIGIN OF THE SOLAR SYSTEM

Almost all observed astronomical formations can be placed in the evolutionary sequence we have just discussed, either with fair certainty or with reasonable plausibility, except for one outstanding and conspicuous exception—the Solar System. Cosmogony came into being as an attempt to discover the origin of the solar system. The reasons why it limited its efforts to this particular problem are chronological; in the early days of cosmogony, astronomy was barely conscious of anything outside the solar system. The sketch just given of the findings of modern scientific cosmogony has been remarkable in that it has exhibited cosmogony taking us a tour round the whole universe, explaining the origin and life-history of practically every object we encounter on this tour, and then becoming speechless when it is brought back home and confronted with its birth place, the solar system.

LAPLACE'S NEBULAR HYPOTHESIS. The first serious scientific cosmogony was that embodied in the famous Nebular Hypothesis of Laplace. In 1755 Kant had pictured a primaeval chaos condensing into spinning nebulae, and, identifying one of these nebulae with the sun, had imagined the planets to be formed by the solidification of masses of gas shed from the nebula, much in the way in which we have supposed the stars to be born. In 1796 Laplace advanced similar ideas,

which he developed in detail with a mathematical precision quite beyond the capacities of Kant. He shewed how, as its shrinkage made it spin ever faster and faster, a rotating mass of gas would gradually flatten out, develop the lenticular form we have already discussed (fig. 3 of Plate XX), and then proceed to eject matter in its equatorial plane, or rather to leave it behind as the shrinkage of the main mass continued. At this stage it would look somewhat like the nebulae shewn in figs. 4 and 5 of Plate XX, although Laplace, being unacquainted with nebulae of this type, adduced Saturn surrounded by its rings as an example of the formation to be expected at this stage (Plate XXIX, p. 272). Laplace imagined that the fringe of abandoned gas would then condense and form a single planet. As the main mass shrunk further, more gas was abandoned in the equatorial plane, which in due course condensed into another planet, and so on, until the sun left off shrinking and no more planets were born. A repetition of the same process, but on a far smaller scale, resulted in the satellites being born out of the planets.

That the hypothesis is *prima facie* plausible, is evident from its having survived, and indeed been generally accepted, for nearly a century before it encountered any serious opposition. Recently criticisms have accumulated, of so vital a nature as to make it clear that the hypothesis must be abandoned.

The sun, according to Laplace, broke up and gave birth to planets through excess of rotation. Yet both theory and observation indicate quite clearly the fate in store for a star which rotates too fast for safety; it does not found a family, but merely bursts, like an overdriven fly-wheel, into parts of nearly equal size. Spectroscopic binary and multiple systems are the relics of stars which have broken up through excess of rotation, and they do not in the least resemble the solar system.

Again, the principle of "conservation of angular momentum" requires that the rotation of the primaeval sun shall persist in the rotation of the present sun, and in the revolutions of the planets around it. On adding together the contributions from all of these, we obtain a total which ought to represent the angular momentum of the primaeval sun. In strictness a further contribution ought to be added on account of the weight of all the radiation which the sun has emitted since the planets were born. We can calculate the amount of this contribution, because we know the age of the earth with tolerable accuracy, but it proves to be entirely negligible.

The total angular momentum of the primaeval sun can be calculated with very fair accuracy, because something like 95 per cent. of the total angular momentum of the present solar system resides in the orbital motion of the four major planets, Jupiter alone contributing 60 per cent. The contributions from these four planets can of course be calculated with great exactness, so that some uncertainty in the minor contributions which make up the remaining 5 per cent. can have but little influence on the total.

When this total is calculated the startling fact emerges that the primaeval sun cannot have had enough rotation to cause break-up at all. Clearly the sun is very far from being broken up by its present rotation. Flattening of figure is the first step towards break-up, and the sun's figure is so little flattened by its present rotation that the most refined measurements have so far failed to detect any flattening at all. On adding the further angular momentum now represented in the motions of Jupiter and all the other members of the solar system, we arrive at a primaeval sun rotating about as fast as Jupiter or Saturn now rotate, and shewing about the same degree of flattening of figure as

Jupiter—enough to measure quite easily in a telescope, or even to detect with the eye alone, but nothing like enough to cause break-up.

The sun is hardly likely to have altered much since its planets were born, for the intervening 2000 million years or so represent but a minute fraction of the sun's total life. If, however, we imagine it to have shrunk appreciably in the interval, then the available amount of angular momentum would have been even more unable to break up the large primaeval sun than it is to break up the present shrunken sun. Whichever way we look at it, we reach the conclusion that the sun cannot have broken up, as Laplace imagined, through excess of rotation; indeed, it can never have possessed more than a quite tiny fraction of the amount of rotation needed to break it up.

A third objection is of a somewhat different character. Laplace was a very great mathematician, and there was nothing the matter with his abstract mathematical theory, so far as it went. More refined modern analysis has confirmed it at every step, and observation does the same, as photographs of rotating nebulae (Plate XX) bear witness. These photographs exhibit a process taking place before our eyes, which is essentially identical with that imagined by Laplace, except for a colossal difference of scale. Everything happens qualitatively as Laplace imagined, but on a scale incomparably grander than he ever dreamed of. In these photographs the primitive nebula is not a single sun in the making, but contains substance sufficient to form hundreds of millions of suns; the condensations do not form puny planets of the size of our earth, but are themselves suns; they are not eight or so in number, but must be counted in millions.

We may ask why the same thing cannot happen on the smaller scale imagined by Laplace—for are not the

conclusions of mathematics applicable independently of the size of the body with which we are dealing? The answer has in effect been given already (p. 238). Everything happens on the smaller scale according to plan until we come to the formation of the condensations; here the question of scale proves to be vital. We have seen (p. 215) how the molecules which form the sun have condensed into a star because of their great number; the molecules in a room do not condense into anything at all because they are too few. In the same way, the molecules left behind by the slow shrinkage of a sun (assuming this for the moment to rotate rapidly enough to leave molecules behind) would not condense, because at any instant there would be too few of them available for condensation. They would be shed by driblets, and a driblet of gas does not condense but scatters into space. A mathematical calculation decides the question definitely; it is of a kind which Laplace could not make, since he was unacquainted with the molecular properties of gases. The decision is entirely adverse to his hypothesis. Apart from minor details, the process imagined by Laplace explains the birth of suns out of nebulae; it cannot explain the birth of planets out of suns.

SECOND BODY THEORIES. Laplace imagined his sun to be alone in space, even its nearest neighbours being too remote to influence it in any way. It was the natural supposition to make; we have already remarked how exceedingly rare an event it must be for two stars to approach near enough to influence one another. Yet no possible mode of evolution of a star which remains alone in space seems able to explain the origin of the solar system. As far back as 1750 Buffon had suggested that the solar system might have been produced through the disruption of the sun by another body, which he described as a "comet." In propounding

his Nebular Hypothesis, Laplace mentioned Buffon's idea, but dismissed it somewhat curtly on the grounds that it seemed unable to account for the nearly circular orbits of the planets—an ill-founded objection, as we shall soon see. Yet when we find that a single star cannot of itself give birth to a solar system, it becomes natural to investigate what happens on the rare occasions on which the evolution of a star is directed along other paths by the near approach of a second star.

In 1880 Professor A. W. Bickerton, reviving Buffon's idea, supposed that the solar system had been formed by the collision of the sun with another star. He imagined the *débris* of the collision to form a third nebulous body, condensations in which formed the planets. He shewed how the resistance which the planets would encounter as they moved through the surrounding nebula would gradually make their orbits more circular, and so account for their present nearly circular shapes. Ten years earlier the English writer, R. A. Proctor, had advanced similar ideas, although with less precision. In 1898 a Cambridge mathematician, W. F. Sedgwick, replaced the concept of material collision by that of tidal action; he propounded a theory according to which the planets were pulled out of the sun by the tidal force of a passing star. In 1901 I independently advanced a similar speculation. Still a third speculation on these lines was put forward in 1905 by Professors Chamberlin and Moulton of the University of Chicago. They supposed that a passing star exerted a powerful tidal pull on the sun, with the result that the ordinary solar prominences temporarily attained an extraordinary violence; the ejected matter was supposed to rise to unusual heights and condense into small solid bodies, the "planetesimals," out of the aggregation of which the planets were ultimately formed. These various theories were all purely speculative. They have shewn

very little capacity either for surviving the acid test of mathematical analysis, or for explaining the more salient features of the solar system; none of them, for instance, explains why the larger planets in the solar system are accompanied by families of satellites. In 1916 I investigated mathematically what would actually happen when one star raised violent tidal forces on another, and obtained results which seemed to me to demolish the planetesimal theory of Chamberlin and Moulton, and led me to put forward an alternative "Tidal Theory," which I believe a large proportion of astronomers now accept as giving the *most probable* origin of the solar system; it can of course make no claim to finality or certainty.

TIDAL THEORY. When two stars or other bodies pass close to one another without collision, each will raise tides in the other. The closer the approach, the higher the tides in general, although something must depend also on the speed with which the bodies pass one another, because this determines the length of time during which they influence one another.

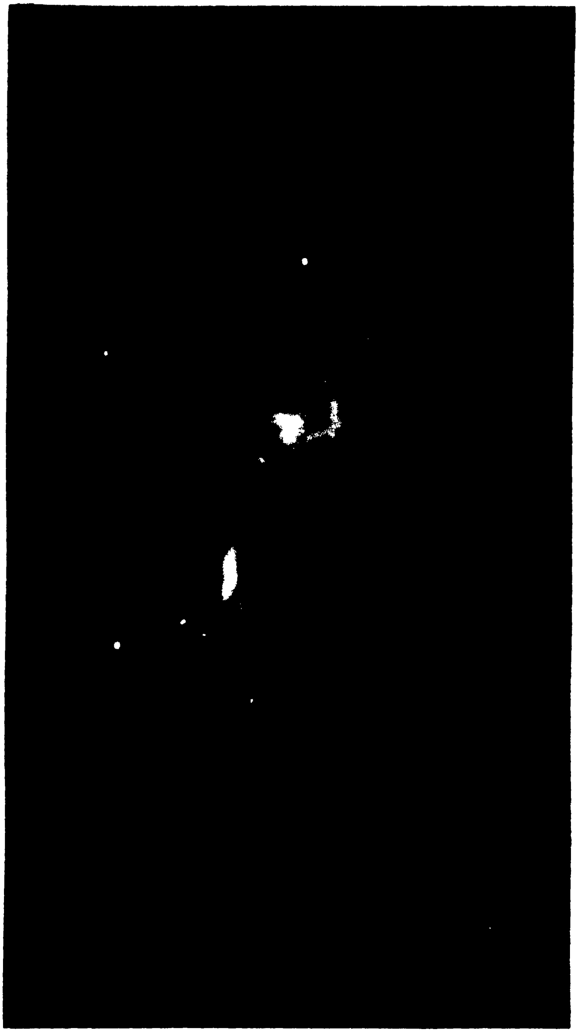
It is likely that the two spiral arms which give their name and characteristic appearance to the spiral nebulae may owe their inception to a somewhat similar tidal action. Conditions here are different in that the rotation of the nebulae in any case causes them to emit matter in their equatorial planes, so that even small tidal forces should then cause this matter to concentrate in two symmetrical arms. Under stellar conditions a far closer approach is necessary to draw matter out from the star, and there will then be two unequal and dissimilar arms, or possibly only one arm.

If the approach is very close indeed, the tides may assume an entirely different aspect from the feeble tides which the sun and moon raise in our oceans; they may take the exaggerated forms of high mountains of matter

moving over the surface of the star. An even closer approach may transform these mountains into long arms of gas drawn out from the body of the star. When the two stars are unequal in weight, the lesser may be expected to suffer more disturbance than the weightier.

THE BIRTH OF PLANETS. The long arm or filament of matter drawn out of a star by tidal action is at first continuous in its structure, but analysis shews that it provides a fit subject for the operation of what we have called gravitational instability. Condensations begin to form in this long arm of gas, in the way already described. As before, the smaller condensations are dissipated, while the larger increase in intensity until finally the filament breaks up into a number of detached masses. Calculations of the kind explained on p. 220 shew that these would be comparable in weight to the planets of the solar system, so that we may henceforth describe them as planets. The pairs of nebulae shewn in Plate XXVII and the upper half of Plate XXVIII are very probably under one another's tidal influence, and may serve to suggest the general nature of the process we are now considering, although it must be remembered that whatever is happening here is on an enormously greater scale than that of the solar system—if it were not, the telescope would be utterly unable to shew it to us.

When the new-born planets first begin to move as separate and independent bodies, they are acted on by the gravitational pulls of both stars, and so describe highly complicated orbits. Gradually the bigger star recedes until its gravitational effect becomes negligible, and the planets are left describing orbits around the smaller star alone. If the planets moved in a clear field of empty space, these orbits would be exact ellipses. But the great cataclysm which has just occurred must have



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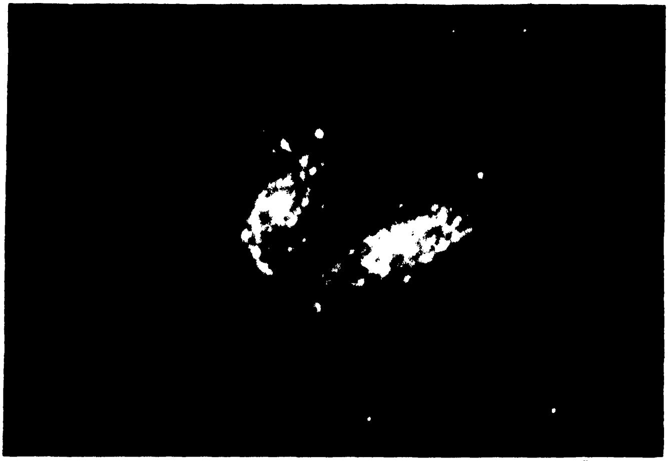
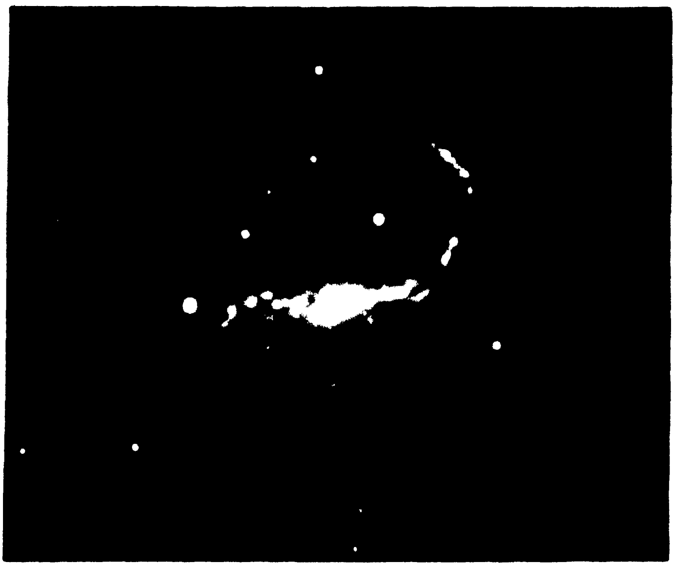
Two Nebulae (N.G.C. 4395, 4401) suggestive of Tidal Action



The twin Nebulae N.G.C. 4567–8



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The Nebula N.G.C. 7479

left all sorts of *débris* behind. Comets, meteors and other minor bodies which still survive in the solar system may represent a small part of it, but probably the main part was left in the form of dust or gas, so that the new-born planets had at first to plough their way through a medium which offered some resistance to their motions. Under these circumstances their orbits would not be strict ellipses. It can be proved that a resistance of the kind just described would change the shape of the orbits, and that with the progress of time they would become more circular, finally becoming absolutely circular if the medium should last long enough.

The *débris* of gas and dust would, however, continually be swept up by the planets and would disappear completely in time, probably leaving the planetary orbits something short of absolute circles. Assuming that all this has happened in the solar system, very little of the original *débris* can now remain, its last vestiges being probably represented by the particles of dust which are responsible for the zodiacal light. Nevertheless, the resisting medium appears to have existed for long enough to make the orbits, both of the planets and of their satellites, very nearly circular for the most part.

The exceptional cases are fully as significant as the cases of conformity. Comparatively elongated orbits still exist in just those regions where we should expect the primaeval resisting medium to have been most sparsely spread in space, namely on the outermost confines of the solar system and of the various satellite systems. Pluto, the outermost planet of all, has a more elongated orbit than any other planet. Again, in the systems of Jupiter and Saturn, the satellites with the most elongated orbits are those which are farthest away from their primaries. In addition to this, a general

tendency may be discerned for elongated orbits to be associated with small weights, both in planets and their satellites. Mercury, with a weight of only a twenty-fifth that of the earth, has a quite elongated orbit, as also to a less degree has Mars, with a ninth of the weight of the earth. An explanation of this has been suggested by Jeffreys. Massive planets such as Jupiter and Saturn must have collected a large mass of the resisting medium round them, and carried it through space with them as a far-reaching envelope. The massive planets would have their motion checked by the interaction of the whole of this big envelope with the remainder of the medium, and so would attain circular orbits more rapidly than the lighter planets which had accumulated envelopes of very much smaller dimensions. And the same, with the appropriate modifications, is true of the satellite systems.

Jeffreys has calculated the rate at which planetary orbits would change their shape under the action of this resisting medium. The data of the problem are necessarily uncertain, and this uncertainty naturally affects his conclusions, but we have already seen (p. 174) that his study has yielded a valuable confirmation of other estimates of the length of time which has elapsed since the planets were born.

We may next turn our attention to the physical changes which must all this time be affecting the various planets. The long filament of matter pulled out of the sun is likely to have been richest in matter in its middle parts, these parts having been pulled out when the second star was nearest and its gravitational pull was strongest. Diagrammatically at least, we may think of this filament as shaped like a cigar—thick near the middle, thin at the ends—so that when condensations begin to form, those near the middle are likely to be richer in matter than those at the ends. This probably

explains why the two most massive planets, Jupiter and Saturn, occupy the middle positions in the sequence of planets.

Fig. 13 shews the planets arranged in the order of their distances from the sun, with their sizes drawn roughly to scale. The thousands of asteroids whose orbits now fill the space between the orbits of Mars and Jupiter are represented as a single planet, it being generally supposed that these asteroids were formed by the break-up of what was originally a single planet in a way we shall shortly describe.

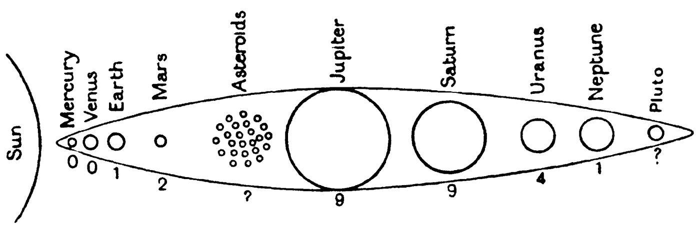

Fig. 13. Diagrammatic scheme shewing the birth of planets out of a cigar-shaped filament of gas. The number of satellites is indicated under each planet (see p. 261).

If we surround the planets by a continuous outline, as in the diagram, we can reconstruct in imagination the cigar-shaped filament out of which they were produced, and we see at once how the biggest planets were produced where matter was most abundant.

The tidal theory which predicts all these features had been propounded, and its consequences worked out, many years before the new planet Pluto had been discovered. Valuable support for the theory may thus be found in the circumstance that Pluto behaves in every way according to the requirements of the tidal theory.

THE BIRTH OF SATELLITES. We have already noticed how the great disparity of weight between the sun and planets distinguishes the sun-planet formation

arrangement of the satellite systems becomes very apparent, and this arrangement is seen to be exactly in accordance with the prediction of the tidal theory. The cigar-shaped arrangement applies not only to the sizes of the planets, but also, as it ought, to the numbers of their satellites.

The earth and Neptune, with only one satellite each, and those comparatively large ones, form the obvious lines of demarcation between planets which were originally liquid and those which were originally gaseous. This leads us to conjecture that Mercury, Venus and Pluto must have become liquid or solid immediately after birth, that the earth and Neptune were partly liquid and partly gaseous, and that Mars, Jupiter, Saturn and Uranus were born gaseous and remained gaseous at least until after the birth of their families of satellites.

We may perhaps find further evidence confirmatory of the tidal theory in the circumstance that the weights of Mars and Uranus are abnormally small for their positions in the sequence of planets. If, as we have supposed, the planets were all born out of a continuous filament of matter, the weight of Mars at birth would in all probability have been intermediate between those of the earth and Jupiter, and the weight of Uranus intermediate between those of Neptune and Saturn. But if, as we have already been led to suppose, the two anomalous planets Mars and Uranus were the two smallest planets to be born in the gaseous state, they would be likely to lose more of their substance than the other planets through their outermost layers of molecules dissipating away into space before they had cooled down into the liquid state. If Mars and Uranus are supposed to be mere relics of planets which were initially far more massive than they now are, the anomalies begin to disappear and the pieces

of the puzzle to fit together in a very satisfactory manner.

ORBITAL PLANES. Every rotating mass, whether gaseous, liquid or solid, has a definite axis of rotation, and, perpendicular to this, a definite equatorial plane which divides the mass symmetrically into two exactly equal and similar halves. When a mass breaks up under its own rotation, the equatorial plane and the symmetry still persist. Illustrations of this can be found in any set of photographs of rotating nebulae, as, for instance, those shewn in Plates XV and XVI. In more humble life an illustration is provided by the splashes of mud thrown off by a spinning bicycle-wheel, which all keep in the plane in which the wheel is spinning.

If the sun's equatorial plane had proved to be a plane of symmetry for the solar system, so that the whole system was similarly arranged as regards the two sides of this plane, it might have been possible to explain the system as the result of a rotational break-up. But the sun's equatorial plane is not a plane of symmetry. The planets do not move in it; most of them move in a plane which makes an angle of 5 or 6 degrees with it. In terms of our humble analogy, the splashes of mud are not flying about in the plane in which the bicycle-wheel is spinning.

The hypothesis that the planets came into being through a rotational break-up of the sun fails completely before this fact, but the tidal theory provides a simple explanation of it at once. The sun is still rotating much as it was before the planets were born, and so retains its original equatorial plane. The quite different plane in, or very close to, which the planets are describing orbits must clearly be the plane in which the long tidal filament was originally drawn out by the passing star. Thus the plane in which the outer planets now move must record the position of the plane in

which the two stars, the sun and the wandering star, the second parent of the sun's family of children, described orbits about one another 2000 million years ago. It is the only clue the latter has left of his identity, and is of course far too slight to make identification possible after this long lapse of time.

ROTATION. As Jeffreys first pointed out, there is some difficulty in accounting for the rapid rotations of Mars, Jupiter and the other great planets in terms of the tidal theory. We have to suppose that the substance of these planets originally formed part of the sun, that it afterwards expanded to the low density of the tidal filament, and subsequently contracted again to the densities of the present planets, which broadly speaking are not very different in density from the sun.

If no new rotation had been generated in this planetary matter, then the principle of the "conservation of angular momentum" would require that the final speeds of rotation of the planets should be comparable with that of the outer layers of the sun from which the planetary matter originally came. Actually Jupiter, Saturn and Uranus all rotate about 60 times as fast as the sun, and Mars about 24 times as fast, while the inner planets would very possibly shew an equally rapid rotation, were it not for the braking effects of tidal friction.

New rotation may, however, have been generated by the sun's gravitational pull on the filaments of matter out of which the planetary satellites were formed. That part of a filament which did not condense into satellites would ultimately fall back into the planet from which it had emerged and increase the rotation of the planet by so doing. Jeffreys calculates that, to account for the present rotation of Jupiter, no less than a fourteenth of its total mass must have been reabsorbed

in this way—four hundred times the combined mass of all the satellites.

The difficulty does not seem at all fatal to the tidal theory—if for no other reason, because it is impossible to estimate what the original masses of Jupiter's satellites were when they were first born, before their outermost layers of gas had been dissipated away into space. Jeffreys, however, prefers to replace the tidal encounters of the theory by actual collisions, in which rotation was set up by the rubbing past one another of the surfaces of the two bodies involved. With this change it at once becomes possible to account for the rotations of the planets, but only at a price—much, if not all, of the law and order we find in the solar system, of which the tidal theory provided a natural explanation, must on the new theory be attributed to chance and coincidence. The new theory does not explain why the planets should possess satellites at all, and still less why their numbers should shew the regular increase and decrease, as we pass outwards from the sun, which is actually observed.

GRAVITATIONAL INSTABILITY. Reviewing the conclusions of the present chapter, we have seen that the greater part of the universe has been carved out through the birth of successive generations of astronomical bodies under the action of "gravitational instability."

The normal genealogy runs somewhat as follows:

chaos—nebulae—stars—binary systems—sub-systems.

Not all stars have passed on to the last two generations; where only a small amount of rotation was present, a star might well live its whole life without further subdivision. Our sun would have provided an instance of this had it not been for the rare accident of the close approach of a second star. From the inter-

action of these, two other generations came into being, still through the mechanism of gravitational instability. For our solar system, as for any other similar systems there may be in the sky, the genealogy runs as follows:

chaos—nebula—sun—planets—satellites.

Both types of genealogy shew five generations, each born from its parent through the action of gravitational instability, and between them the two genealogies include practically all the large-size astronomical objects with which we are acquainted. It is then fair to say that gravitational instability appears to be the agency primarily responsible for the main architecture of the universe.

ROCHE'S LIMIT

The reign of gravitational instability must end with the birth of planetary satellites, since gaseous bodies of less weight than these could not hold together. Even under the most favourable circumstances their feeble gravitational pulls would be unable to restrain their outermost molecules from escaping, so that the whole mass would speedily scatter into space. Yet astronomy provides many instances of smaller bodies; we have already mentioned the asteroids, meteors or shooting-stars, and the particles of Saturn's rings. As all these are too small to have been born in the gaseous state, we must suppose them to be the broken-up fragments of larger masses. This accords with the circumstance that these small bodies as a rule do not occur individually but in swarms.

The asteroids occur as a single swarm. If these were found scattered throughout the solar system, their origin might present a difficult problem. As things are, the whole swarm can be explained quite simply as the broken fragments of a primaeval planet. Saturn's

rings again admit of a natural explanation as the fragments of a former shattered moon of Saturn. Comets, which we have hardly had occasion to mention so far, are in all probability swarms of minute bodies which are just held together sufficiently by their mutual gravitational attraction to describe a common orbit in space. At its apparition in 1909, Halley's comet was estimated to reflect as much of the sun's light as a single body 25 miles in diameter. Yet its apparent surface was 300,000 times that of such a body, and was quite transparent. It is difficult to resist the conclusion that the comet consisted of a widely spaced swarm of small bodies, and such a swarm again admits of a simple explanation as the broken fragments of a single mass.

Shooting-stars, or meteors, also are encountered in swarms. As we shall see later, the motion of many of these swarms makes it possible to identify them as broken-up comets. Thus the broken fragments which compose a comet are identical with the meteors which we see as shooting-stars when they penetrate into the earth's atmosphere. Shapley has estimated that the earth's atmosphere must catch thousands of millions of shooting-stars every day, of which at most only one in a hundred is bright enough to be visible to the naked eye. Generally they dissolve into vapour before they reach the earth's surface (see p. 196); occasionally one is so big that the earth's atmosphere fails to dissipate it entirely, and what remains of it strikes the earth as a solid body—a meteorite. Every shooting-star and meteorite may be regarded as a miniature comet, consisting of only a single fragment. On occasions a whole group of fragments, moving in parallel paths at only small distances apart, may strike the earth's atmosphere and appear as a "fireball." Generally speaking all the small fry of the solar system move in swarms,

and can be naturally interpreted as the broken-up fragments of larger bodies.

If the meteorites are broken fragments of bodies which were born out of the sun at the same time as the planets, they must have solidified at about the same time as the earth, at an epoch which we have placed at about 2000 million years ago. But if they had been born out of some other star, the time of their solidification might have been anywhere up to millions of millions of years ago.

Professor Paneth and two colleagues at Königsberg have recently estimated the ages of various meteoric stones by methods similar to those employed to fix the age of the earth (p. 171). They obtain ages which range from a few million years up to 2900 million years, but there is nothing beyond this last figure. Not a single stone suggests an age even approaching millions of millions of years. This provides very strong evidence that these stones were products of the same cataclysm as produced the earth, and incidentally provides valuable confirmation of our previous estimate of the earth's age.

We can easily see how larger bodies might be broken up into swarms of meteors. We have supposed the sun to have been broken up, at least to the extent of ejecting a family of planets, by the tidal pull of a passing star. What would have happened if the passing star had not passed, but had come to stay? So long as it remained within a certain distance of the sun, its tidal forces were pulling the sun to pieces. We can imagine how a longer visit from it would have resulted in a greater upheaval in the sun, and the birth of a larger family of planets. Finally a visit of unlimited duration would have shattered the sun into fragments.

In 1850 Roche gave a mathematical investigation of this process of tidal break-up. His discussion dealt

only with solid or liquid bodies, but the underlying mechanism is the same whether the bodies are solid, liquid or gaseous. We have seen that the smaller of the two bodies involved in a tidal encounter suffers the most. Roche dealt only with the case in which one body was very small in comparison with the other; in such a case the small body was completely broken up, while the larger one remained unscathed. Roche imagined the small body to describe an orbit of gradually decreasing size around the big body. He calculated that if the two bodies were of equal density, the small body would be broken up as soon as the radius of its orbit fell to 2·45 times the radius of the large body. If the bodies are different in density the matter is slightly more complicated. We must imagine the larger body to expand or contract until it has the same average density as the smaller body; the critical distance is then 2·45 radii of the larger body in its imaginary expanded or contracted state.

This distance is generally known as Roche's limit. A satellite can describe a circular orbit about its primary with safety so long as this orbit lies beyond Roche's limit, but it is broken into fragments as soon as it trespasses within the limit. The following figures confirm Roche's mathematical analysis:

Radius of Saturn's outermost ring	2·30 radii of Saturn
Roche's limit	*2·45 radii of primary*
Radius of orbit of Saturn's innermost satellite	3·11 radii of Saturn
Radius of orbit of Jupiter's innermost satellite	2·54 radii of Jupiter
Radius of orbit of Mars' innermost satellite	2·79 radii of Mars

They also suggest very forcibly that Saturn's rings are the broken-up fragments of a former satellite which ventured into the danger-zone marked out by Roche's limit. We speak of rings in the plural, because two circular gaps cause an appearance of three detached

rings. There is a tendency to jump to the hasty inference that the rings are the shattered remains of three distinct satellites, but it is not so. Certain orbits around Saturn appear to be rendered unstable by the motions of the larger satellites of Saturn, so that no particle could permanently remain in such an orbit. He has calculated positions for these unstable orbits, and these are found to agree exactly with the positions of the observed divisions between the rings. Thus Saturn's rings were in all probability produced by the breakage of a single satellite.

Roche's fundamental idea can be extended in many directions and admits of varied applications. There must, for instance, be a danger-zone, marked off by a Roche's limit, surrounding the sun. The distance of this danger-zone from the sun depends on the density of the body for which it is dangerous (p. 269). For a body having the low density of a comet the distance will be very great indeed. Whatever the distances of their danger-zones, comets must occasionally pass through them and become broken up in so doing. Two comets, Biela's comet (1846) and Taylor's comet (1916), were observed actually to break in two while at about the earth's distance from the sun, and in 1882 a comet was seen to divide into four parts. Biela's comet returned in due course (1852) in the form of two distinct comets a million and a half miles apart, since which time neither part of the original comet has been seen again. The orbit of this comet was identical with that of the Andromedid meteors, which make a display of shooting-stars in the earth's atmosphere on favourable 27ths of November, so that it is likely that these shooting-stars are the broken remains of Biela's comet. Other conspicuous swarms of shooting-stars also move in the tracks of comets—the Leonids, which used to make a magnificent show every 33 years, move in the

track of Comet 1866 I, the Perseids in the track of another Comet (1862 II), and the Aquarids in the track of Halley's famous comet. In each case there can be little doubt that the shooting-stars are scattered fragments of the comets. Besides this there are several families of comets whose members follow one another round and round in the same orbit, as though they had originally formed a single mass.

In the same way a Roche's limit must surround the planet Jupiter, so that comets and other bodies may be broken up through getting inside the danger-zone marked off by this limit. Jupiter's innermost satellite is already perilously near it. But the greatest interest of this particular danger-zone is that it probably accounts for the existence of the asteroids. In the early days of the solar system, when the orbits of the planets were less nearly circular than they now are, a primaeval planet between Mars and Jupiter may well have described an orbit so elongated as to take it repeatedly within the danger-zone of Jupiter. If so, we need look no further for the origin of the asteroids. It is significant that the average orbit of all the asteroids agrees almost exactly with that of the planet which Bode's law (p. 21) would require to exist between Mars and Jupiter.

As a final illustration, such a danger-zone must also surround the earth. The moon is at present well outside it, but will not always be so. For we have already seen (p. 243) that the final fate in store for the moon is to be dragged back, under the influence of the earth's tides, towards the earth from which it originally came. When it has been dragged down to within about 8000 miles of the surface of the earth, the tides raised by the earth in the solid body of the moon will shatter the latter into fragments. These will form a system of tiny satellites revolving around the earth in the same way

as the particles of Saturn's rings revolve around Saturn, or as the asteroids revolve around the sun.

Moonlight will be replaced by the light reflected from the earth's ring of satellites. This will be far brighter than our present moonlight because of the far greater surface which will reflect the sun's light.

Saturn in 1916

Saturn in 1917

Lowell Observatory

Saturn in 1921

Saturn and its System of Rings

CHAPTER V

Stars

The process of carving out the universe which we considered in the last chapter ends normally with a simple star, although special accidents may have other consequences. As the result of close approaches with other stars, a tiny fraction of the total number of the stars, perhaps about one star in 100,000 (p. 359 below), may be attended by a retinue of planets. Another fraction, still small, although far greater than the foregoing, appears to have broken up as the result of excessive rotation, and formed binary or perchance multiple systems. But the destiny of the majority of stars is to pursue their paths solitary through space, neither breaking up of themselves nor being broken up by other stars. The only contact such stars have with the outer universe is that they are incessantly pouring away radiation into space. This outpouring of radiation is almost entirely a one-way process, any radiation a star may receive from other stars being quite inappreciable in comparison with the amount it is itself emitting. We have seen (p. 198) how this radiation is accompanied by a loss of weight, and this again is all give and no take, the weight of any stray matter the star may sweep up out of space, like that of any radiation it receives, being quite inappreciably in comparison with the weight it loses by radiation. Without unduly straining the facts, the normal object in the sky may be idealised as a solitary body, alone in endless space, which continually pours out radiation and receives nothing in return.

In the present chapter we shall consider the sequence of changes which such a star may be expected to

experience during the course of its life. Having already discussed the mechanical accidents to which stars are liable, namely, fission through rotation and break-up through the tidal action of a passing star, we now turn to consider the life of a normal star which escapes all accidents until it finally becomes extinct through mere old age.

It will be necessary in the first place to describe the physical states of the various types of stars observed in the sky, and as a preliminary to this we must explain how the observations of the astronomer are translated into a form which gives us direct information as to the condition of the star.

SURFACE-TEMPERATURE. In Chapter II (p. 156) we saw how each colour of light or wave-length of radiation has a special temperature associated with it, light of this colour predominating when a body is heated up to the temperature in question. For instance, a body raised to what we call a red heat emits more red light than light of any other colour, and so looks red to the eye.

Thus if a star looks red, it is legitimate to infer that its surface is at the temperature we describe as a red heat. If another star has the colour of the carbon of an arc-light, we may conclude that its surface is at about the same temperature as the arc. In this way we can estimate the temperatures of the surfaces of the stars.

In practice the procedure is not so crude as the foregoing description might seem to imply. The astronomer passes the light from a star through a spectroscope, thus analysing it into its different colours. By a process of exact measurement, he then determines the proportions in which the different colours of light occur. This shews at once which colour of light is most plentiful in the spectrum of the star. Either from this or

from the general distribution of colours, he can deduce the temperature of the star's surface.

We have already seen (p. 142) how Planck discovered the law according to which the radiation emitted by a full radiator is distributed amongst the different colours or wave-lengths of the spectrum. The four curves shewn in fig. 14 represent the theoretical

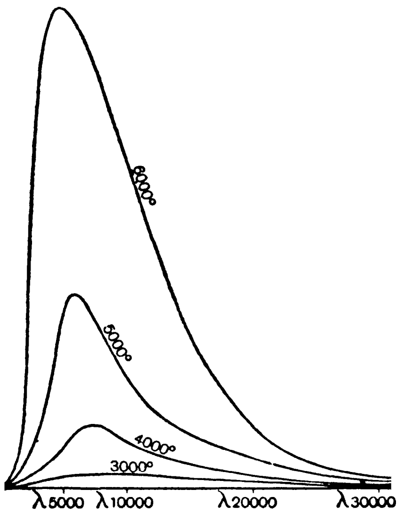

Fig. 14. Distribution of radiation of different wave-lengths at various temperatures.

distribution for the radiation emitted by surfaces at the four temperatures 3000, 4000, 5000 and 6000 degrees respectively. The different wave-lengths of light are represented by points on the horizontal axis, the marked wave-lengths being measured in the unit of a hundred-millionth part of a centimetre, which is usually called an Angstrom. The height of the curve above such a point represents the abundance of radiation of the wave-length in question.

The two methods of determining stellar temperature will be easily understood by reference to these curves. The 6000 degrees curve reaches its greatest height at a wave-length of 4800 Angstroms, so that if light of wave-length 4800 Angstroms proves to be most abundant in the spectrum of any star, we know that the star's surface has a temperature of 6000 degrees. The second method consists merely in examining to which of the theoretical curves shewn in fig. 14 the observed curve can be fitted most closely.

Either of these methods indicates that the temperature of the sun's surface is about 6000 degrees absolute, which is 2000 degrees hotter than the hottest part of the electric arc. The total amount of light and heat received on earth from the sun shews that the sun's radiation must be very nearly, although not quite, the "full temperature radiation" (p. 141) of a body at this temperature. This is also shewn by the sun's radiation being distributed among the various colours in a way which conforms very closely to the theoretical curve for a full radiator at 6000 degrees shewn in fig. 14.

We have seen that the spectral type of star (p. 55) is determined mainly by the surface-temperature of the star, whence it follows that the surface-temperature of a star can also be estimated from its spectral type. Many of the lines in stellar spectra are emitted by atoms from which one or more electrons have been torn off by the heat of the star's atmosphere. We know the temperatures at which the electrons in question are first stripped off their atoms, and so can deduce the star's temperature.

The temperatures which correspond to the different types of stellar spectra as shewn in Plate IX (p. 55), are approximately as follows:

Spectral type	Temperature
B	20,000
A	10,000
F	7,000
G	6,000
K	5,100
M	3,400

The last three entries in the table refer only to normal stars having diameters comparable with that of the sun. We shall find (p. 294) that a second class of stars (giants) exist, whose diameters are enormously greater than the sun's. These have the substantially lower temperatures shewn below:

Spectral type	Temperature
G	5600
K	4200
M	3200

The surface temperatures of stars of type *O* (p. 55) are known with less accuracy, but are certainly higher than any of those just given and appear to cover the whole range from 20,000 degrees to about 75,000 degrees. Novae when at their brightest (p. 68) belong to this spectral type, as do also the nuclei of the planetary nebulae (p. 30). Zanstra, who has made a special study of the latter, finds that the average surface-temperature of 18 nuclei is 42,000 degrees. Beals finds that the temperature of Nova Aquilae when at its brightest must have been about 65,000 degrees, and considers that the majority of novae probably attain to temperatures of this order at their moment of greatest luminosity.

In studying stellar structure and mechanism, the temperature of a star's surface is less immediately

important than the amount of radiation it pours out per square inch.

This of course depends on the temperature; the hotter a surface, the more radiation it emits. But the temperature does not measure the quantity of radiation emitted. If we double the temperature of a surface it emits 16 times, not twice, its previous amount of radiation; the radiation from each square inch of surface varies as the fourth power of the temperature. As a consequence, a star with a surface-temperature of 3000 degrees, or half that of the sun, emits only a sixteenth part as much radiation per square inch as the sun*. The radiation of each star is a compound of light, heat and ultra-violet radiation, and the proportions of these are not the same in different stars; the cooler a star's surface the greater the fraction of its radiation which is emitted as heat. Thus the star at 3000 degrees will emit nothing like as much as a sixteenth of the sun's light per square inch, but will emit more than a sixteenth of the sun's heat.

This shews that the total emission of radiation of a star cannot be estimated from its visual brightness alone; a substantial allowance must always be made for invisible radiations, both for the invisible heat at the red end of the spectrum and for the invisible ultra-violet radiation at the other end. The importance of these corrections is shewn in fig. 15. The four curves are identical with those already given in fig. 14, and shew how the radiation from a star of given surface-temperature is distributed over the different wave-lengths. The total radiation emitted at any temperature is of course represented by the whole area enclosed between the corresponding curve and the horizontal axis. The eye is only sensitive to radiation of wave-

* This is shewn in fig. 14, the area of the 3000 degree curve being only a sixteenth of the area of the 6000 degree curve.

lengths lying between 3750 and 7500 Angstroms, so that of all this radiation only that part in the shaded strip is visible, all the rest representing invisible radiation.

We see at once that a fair proportion of the radiation emitted by a star at 6000 degrees comes within the range of visibility, but only a small fraction of that emitted by a star at 3000 degrees, the main part of this

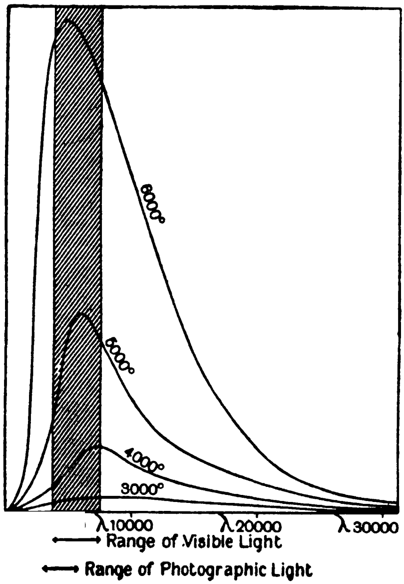

Fig. 15. Distribution of radiation into visible and invisible.

latter radiation being heat-radiation, with a wave-length greater than that of visible light. It is impossible to insert a curve in fig. 15 to shew the distribution of radiation from a star with a surface temperature of 60,000 degrees, because such a curve would be four miles in height, but if such a curve were drawn, we should see that practically all the radiation was ultra-violet radiation with a wave-length shorter than that

of visible light. Taking the stars as a whole, it is fair to say thar star-light forms only a small part of the total radiation of the stars.

If our eyes were suddenly to become sensitive to all kinds of radiation, and not to visual light alone, the appearance of the sky would undergo a strange metamorphosis. The red stars Betelgeux and Antares, which are at present only 12th and 16th in order of brightness, would flash out as the two brightest stars in the sky, while Sirius, at present the brightest of all, would sink to third place. A star in the very undistinguished constellation of Hercules would be seen as the sixth brightest star in the sky. It is the star α Herculis, at present outshone by about 250 stars. As a consequence of its extremely low temperature of 2650 degrees, this star emits its radiation almost entirely in the form of invisible heat. For instance it emits 60 times as much heat as the blue star η Aurigae, whose temperature is about 20,000 degrees, but only four-fifths as much light.

Allowances for invisible radiation have been made in all the calculations referred to in the present book, although it has not been thought necessary continually to restate this.

STELLAR DIAMETERS. It is easy to measure the diameter of most of the planets; with the exception of Pluto these all appear in the telescope as discs of appreciable size. But the stars are too remote for their diameters to be measured in the same way. No star appears larger in the sky than a pin-head held at a distance of four miles, and no telescope yet built can shew an object of this size as a disc. All stars, even the nearest and largest, appear as mere points of light*, so

* The large round images of stars which are often seen in astronomical photographs, as for instance, that shewn in the frontispiece, result merely from over-exposure, and have nothing to do with the sizes of the stars.

that their diameters can only be measured by roundabout methods.

When a star's distance is known, we can tell its luminosity from its apparent brightness. From this, after allowing for invisible radiation, we can deduce the star's total outpouring of energy—so many million million million million horse-power. We also know its outpouring of energy per square inch of surface, because this depends only on its surface temperature which we deduce directly from spectroscopic observation. Knowing these two data, it is a mere matter of simple division to calculate the number of square inches which make up the star's surface, and this immediately tells us the diameter of the star.

The diameters of exceptionally large stars may be measured more directly by an instrument known as the interferometer. When we focus a telescope on a star we do not, strictly speaking, see only a point of light, but a point of light surrounded by a rather elaborate system of rings of alternating light and darkness, called a diffraction pattern. It might be thought that the size of these rings would tell us the size of the star, but the two have nothing to do with one another. The rings represent a mere instrumental defect, their size depending solely on the size and optical arrangement of the telescope. Following a method suggested by Fizeau in 1868, Professor Michelson shewed how even this defect could be turned to useful ends, and by its aid produced what is perhaps the most ingenious and sensational instrument in the service of modern astronomy—the interferometer. In effect, this instrument superposes two separate diffraction patterns of the same star, and sets one off against the other in such a way as to disclose the size of star producing them. The diameters of a few of the largest stars have been measured in this way, so that we may say that we know

their sizes from direct observation. In every case the directly measured diameter agrees fairly well, although not perfectly, with that calculated indirectly in the way already explained. The discrepancies, which are not serious, appear to result from red stars not being accurate "full radiators" in the sense explained on p. 141.

The interferometer method is only available for the largest stars, but at the extreme other end of the scale the theory of relativity has come to the rescue. Einstein shewed it to be a necessary consequence of his theory of relativity that the spectrum of a star should be shifted towards the red end by an amount depending on both the weight and the diameter of the star. If, then, a star's weight is known, the observed spectral shift ought immediately to tell us its diameter. This spectral shift has recently been observed in the light received from the companion of Sirius, and measurements of its amount lead to a value for the star's diameter which agrees tolerably well with that calculated from its luminosity. Thus at both ends of the scale, for the very largest as well as for the very smallest of stars, direct observation confirms the values calculated for the diameters of the stars.

We may accordingly feel every confidence in the calculated diameters of all stars, even when these cannot be checked by direct measurement. Indeed, a discrepancy between the true and calculated diameters could only arise in one way. The diameters are calculated on the assumption that the stars emit their full temperature-radiation. If the stars had been partially transparent like the nebulae, or solid bodies like the moon, this assumption would have been false, and its falsity would at once have been shewn by discordances between the calculated and measured diameters of the stars. The fact that no large discordances appear suggests that the stars emit nearly full tem-

perature-radiation throughout the whole range of size from the largest to the smallest.

THE VARIETY OF STARS

Observation shews that the physical characteristics of the stars vary enormously, so that it is easy, as we shall soon see, to tell a sensational story by contrasting extremes, setting the brightest against the dimmest, the biggest against the smallest, and so on. This would, however, give a very unfair impression of the inhabitants of the sky; it would be like judging a nation from the giants and dwarfs, the strong men and the fasting men, seen inside the showman's tent.

We shall obtain a more balanced impression of the actual degree of diversity shewn by the stars as a whole if we consider the physical states of those stars which are nearest the sun. By taking these precisely in the order in which they come, we avoid any suspicion of going out of our way to introduce stars merely because they are bizarre or exceptional. The small group of stars obtained in this way may be expected to form a fair sample of the stars in the sky, although of course it will not be a large enough sample to include extremes. We need not discuss the sun itself in detail because it will figure as our standard star, with reference to which all comparisons are made.

The System of α Centauri. This system consists of three constituent stars, which are believed to be our three nearest neighbours in space.

The brightest, α Centauri *A*, is very similar to the sun. It is of the same colour and spectral type, but weighs 14 per cent. more and is about 12 per cent. more luminous. Being of the same colour as the sun, it emits the same amount of radiation per square inch. Thus, its 12 per cent. greater luminosity shews that it

must have a surface 12 per cent. greater, and therefore a diameter 6 per cent. greater, than the sun.

The second constituent, α Centauri *B*, is considerably redder than the sun, its surface-temperature being only about 4400 degrees against the sun's 6000 degrees or so. It has 97 per cent. of the sun's weight, but only about a third of its luminosity. Yet, as a consequence of its low temperature, it needs 50 per cent. more area than the sun to discharge a third of the sun's radiation; this makes its diameter 22 per cent. greater than that of the sun. α Centauri *A* and α Centauri *B*

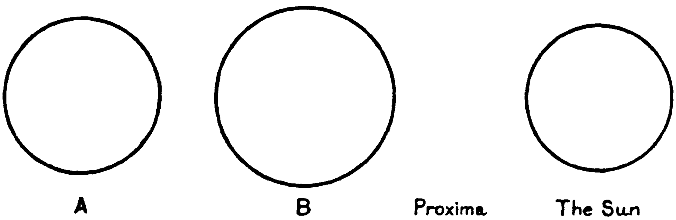

Fig. 16. The System of α Centauri, with the Sun for comparison.

together form a visual binary, the two components revolving about one another in a period of 79 years.

Neither of these two constituents is very dissimilar from the sun, but the third star of the system, Proxima Centauri, is of an altogether different type. It is red in colour, with a surface-temperature of only about 3000 degrees. It is exceedingly dim, emitting only a twenty-thousandth part as much light as the sun, and so has only about a twentieth part of the sun's diameter. Its weight is unknown.

The sizes of the three stars of this system, with that of the sun for comparison, are shewn in fig. 16.

Munich 15040. This is a single faint star about which little is known. Its surface is red, with a temperature probably little above 2500 degrees, and it emits only a twenty-five-hundredth part of the light of the sun.

Wolf 359. This is the faintest star yet discovered, but beyond this very little is known about it. It is red in colour and emits only about a fifty-thousandth part of the light of the sun.

Lalande 21185. Another faint red star, emitting a two-hundredth part of the light of the sun.

The System of Sirius. This consists of two very dissimilar stars, there being some suspicion that a third also may exist.

The principal star, Sirius *A*, which appears as the brightest star in the sky (the Dog-star), is white in colour

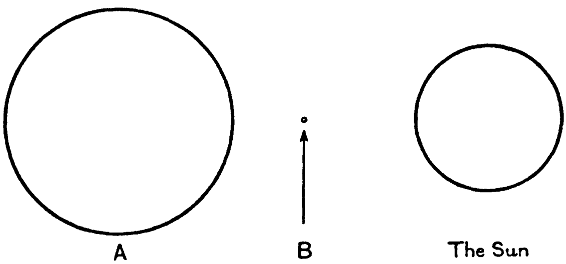

Fig. 17. The System of Sirius, with the Sun for comparison.

and has a surface-temperature of about 11,000 degrees. As this is nearly twice the sun's temperature, Sirius *A* emits nearly 16 times as much radiation per square inch as the sun. Its luminosity is about 26 times that of the sun, and this requires the star's diameter to be 58 per cent. greater than that of the sun. It has nearly four times the sun's volume, but only 2·45 times its weight, so that matter is not as closely packed in Sirius *A* as in the sun. An average cubic metre contains 1·42 tons in the sun, but only 0·88 ton in Sirius *A*.

The faint companion Sirius *B* is one of the most interesting stars in the sky. It is of nearly the same colour and spectral type as Sirius *A*, but emits only a

three-thousandth part as much light. After allowing for the slight difference in surface-temperature, we find that its surface is only one eight-hundredth, and its diameter a twenty-eighth of that of Sirius *A*. Yet Sirius *A* weighs only three times as much as Sirius *B*, although having more than 20,000 times its volume. It is not Sirius *A* but Sirius *B* that is remarkable; the average density of matter in the latter is more than 10,000 times that of water, the average cubic inch containing several hundredweight of matter. Fig. 17 shews the sizes of the two components of Sirius drawn to the same scale as fig. 16.

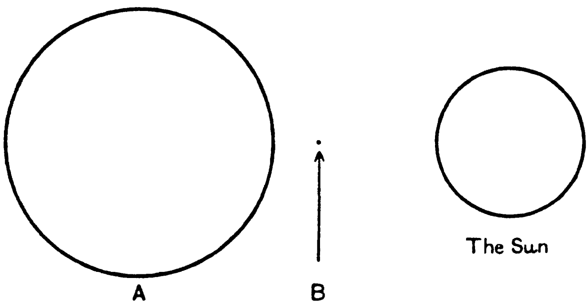

Fig. 18. The System of Procyon, with the Sun for comparison.

B.D. 12° 4523 *and Innes* 11 h. 12 m., 57·2°. Two stars, as to the physical state of which nothing is known, except that they are very faint, emitting a fourteen-hundredth part and a ten-thousandth part of the sun's light respectively.

Cordoba 5 h. 848 and τ *Ceti*. Two faint stars, both of reddish colour, emitting a six-hundredth part and a third of the sun's light respectively.

The System of Procyon. This is a binary system, similar in many respects to Sirius. The main star, Procyon *A*, is of the same general type as the sun, but weighs 24 per cent. more, and emits 5½ times as

much light. Its surface-temperature is about 7000 degrees, and its diameter is 1·80 times that of the sun.

The faint companion, Procyon *B*, is so faint that nothing is known as to its physical condition except that it emits only a thirty-thousandth part of the light of the sun. Its weight is 39 per cent. of the sun's weight.

Fig. 18 shews the sizes of the two components of Procyon on the same scale as before.

Next in order, as we recede from the sun, come eight very undistinguished stars, every one of them redder and fainter than the sun, none of them having

Fig. 19. The System of Kruger 60, with the Sun for comparison.

a surface-temperature higher than 5000 degrees, and none of them emitting more than a quarter of the sun's light. After these we come to

The System of Kruger 60. This is a binary system in which both components are small, red and dim.

The brighter component, Kruger 60 *A*, has a surface-temperature of 3200 degrees, and emits a four-hundredth part of the light of the sun. Its diameter is a third, and its weight a quarter of the sun's, so that its substance must be packed about 7 times as closely as that of the sun.

The fainter component, Kruger 60 *B*, has a similar surface-temperature but emits only a fifteen-hundredth part of the sun's light. Its diameter is a sixth, and its weight a fifth of the sun's, so that its substance must

be packed about 40 times as closely as that of the sun. The system is illustrated in fig. 19.

van Maanen's star. Another very faint star, which has the high surface-temperature of 7000 degrees. Notwithstanding this, it only emits a six-thousandth part of the sun's light. Consequently its diameter is only about a hundred-and-tenth part of the sun's, the star being if anything smaller than the earth. Its weight is unknown, but its substance is in all probability packed even more closely than in Sirius *B*.

The discussion of this sample of stars suggests that the majority of stars in space are smaller, cooler and fainter than the sun. Stars exist which are far brighter than the sun, but they are exceptional, the average star in the sky being a small, dull, dim affair in comparison with our sun.

With this sample of the average population of the sky before us, we may proceed to discuss the various characteristics of stars in a systematic way, without fearing to mention extremes. Let us begin with their weights.

STELLAR WEIGHTS. The two stars of smallest known weight in the whole sky are the faint constituent of Kruger 60, just discussed, and the faintest constituent of the triple system o_2 Eridani, each of which has a fifth of the sun's weight. But the stars whose weights are known are so few that there can be no justification for supposing these to be the smallest weights which occur in the whole universe of stars. A general survey of the situation, on lines to be indicated later (p. 301), suggests that there may be many stars of still smaller weight, but that very few are likely to have weights which are enormously smaller. Probably very few stars weigh as little as a tenth of the sun's weight.

The vast majority of stars have weights inter-

mediate between this and ten times the sun's weight. Stars which weigh even three times as much as the sun are rare, those which weigh ten times as much are very rare, probably only about one star in 100,000 having ten times the weight of the sun. Even higher weights undoubtedly occur—we have already mentioned Plaskett's star, whose two constituents certainly have more than 75 and 63 times the sun's weight respectively, and the quadruple system 27 Canis Majoris whose constituents may possibly each weigh hundreds of times as much as the sun—but such instances are very, very unusual. We may say that as a general rule the weights of the stars lie within the range of from a tenth to ten times the sun's weight, and we shall find that stars differ less in their weights than in most of their other physical characteristics.

LUMINOSITY. A far greater range is shewn, for instance, in the luminosities of the stars—in their candle-powers measured in terms of the sun's candle-power as unity. The most luminous star known is *S* Doradus, already mentioned, with 300,000 times the luminosity of the sun, while the least luminous is Wolf 359 with only a fifty-thousandth part of the luminosity of the sun. The range of stellar luminosities, as of stellar weights, extends about equally on the two sides of the sun, so that the sun is rather a medium star in respect both of weight and luminosity. It is medium in the sense of being about half-way between extremes, but we have seen that there are many more stars below than above it.

In comparison with the very moderate range of stellar weights, the range of luminosity is enormous; *S* Doradus is 15,000,000,000 times as luminous as Wolf 359. If *S* Doradus is a lighthouse, Wolf 359 is something less than a firefly, the sun being an ordinary candle. If the sun suddenly started to emit as much

light and heat as *S* Doradus, the temperature of the earth and everything on it would run up to about 7000 degrees, so that both we and the solid earth would disappear into a cloud of vapour. On the other hand, if the sun's emission of light, and heat were suddenly to sink to that of Wolf 359, people at the earth's equator would find that their new sun only gave as much light and heat at mid-day as a coal fire two hundred yards away; we should all be frozen solid, even the earth's atmosphere being frozen solid around us. So far as we know, there is no possibility of the sun suddenly beginning to behave like *S* Doradus, but we shall see later that the possibility of its behaving like Wolf 359 is not altogether a visionary dream.

SURFACE-TEMPERATURE AND RADIATION. Sirius has been found to have the highest surface-temperature of all the stars near the sun; it is about 11,000 degrees, or nearly double that of the sun. Going farther afield, we find many stars with far higher surface-temperatures. For instance, Plaskett's star is credited with a temperature of 28,000 degrees, the two *O*-type stars of the Wolf-Rayet class* H.D. 191765 and H.D. 192163 with temperatures of the order of 70,000 degrees, and Nova Aquilae at maximum brightness with a temperature of 65,000 degrees. It must, however, be admitted that a substantial element of uncertainty enters into all estimates of very high stellar temperatures.

At the other extreme, stellar temperatures ranging down to about 2500 degrees are comparatively common. The lowest temperatures of all are confined to variable stars of a very special type (long-period variables) in which the light-variation is accompanied by, and indeed mainly arises from, a variation in the tem-

* These are *O*-type stars which shew bright lines in their spectra in place of the more usual dark absorption lines.

perature of the star's surface. The temperature of these stars when at the lowest, ranges down to 1650 degrees, which is but little above the temperature of an ordinary coal fire. In many of them, the temperature varies through a large range, but it never sinks so low that the star becomes completely invisible. Thus there is a range of temperature below about 2500 degrees which no star is known to occupy, except for the long-period variables which only enter it at intervals. This would seem to suggest that the number of absolutely dark stars in the sky is relatively small.

Thus, so far as our present knowledge goes, the temperature of stellar surfaces ranges, in the main, from about 60,000 degrees down to about 2500, the lower limit being extended to about 1650 for long-period variables at their lowest temperatures.

Apart from the long-period variables, this is only a 24 to 1 range, so that the temperatures of the stars are more uniform than either their luminosities or their weights. We must, however, remember that a star's radiation per square inch is far more fundamental than its surface-temperature, and that a 24 to 1 range in the latter involves a range of over 330,000 to 1 in the former. If we include the long-period variables, there is a range of about 1,750,000 to 1 in the emission of radiation per square inch.

In terms of horse-power, the sun emits energy at the rate of 50 horse-power per square inch, a star with a surface-temperature of 1650 degrees emits only a third of a horse-power per square inch, while Plaskett's star, with a surface-temperature of 28,000 degrees, emits about 28,000 horse-power per square inch. In plain English, each square inch of this last star pours out enough energy to keep an Atlantic liner going at full speed, hour after hour, and century after century.

And the energy emitted per square inch by the surface of a star at a temperature of 70,000 degrees is forty times the foregoing—well above a million horse-power per square inch.

SIZE. The four stars of largest known diameter are the following:

Star	Diameter in terms of sun	Diameter in miles
Antares	450	390,000,000
α Herculis	about 400	346,000,000
o Ceti (at max.) ...	300	260,000,000
Betelgeux (maximum)	355	306,000,000
,, (minimum)	210	182,000,000

All these diameters have been measured directly by the interferometer. On the scale used in figs. 16 to 19, in which the sun is about the size of a sixpence, the circle necessary to represent *o* Ceti would be as large as the floor of a good-sized room, while the second star of the system (for *o* Ceti is binary) would be the size of a grain of sand. We may obtain some idea of the immense size of these stars by noticing that every one of their diameters is larger than the diameter of the earth's orbit, so that if the sun were to expand to the size of any one of them we should find ourselves inside it.

These stars must be exceedingly tenuous. Antares, for instance, occupies 90,000,000 times as much space as the sun, so that if its substance were as closely packed, it would weigh 90,000,000 times as much as the sun. Yet, in actual fact, it probably has only about 40 or 50 times the sun's weight, the difference between this number and 90,000,000 arising from the difference between the densities of Antares and the sun. On the average a ton of matter in the sun occupies somewhat less than a cubic yard; in Antares it occupies consider-

ably more space than the interior of Saint Paul's Cathedral. Yet a detailed study of stellar interiors shews that we can attach but little meaning to an average of this sort. It is quite likely that matter at the centre of Antares is packed nearly, although perhaps not quite, as closely as matter at the centre of the sun (p. 312 below). We probably ought to think of the huge size of Antares as being due mainly to an enormously extended atmosphere of very tenuous gas, and there is not much point in striking an average between this and the compact matter at the centre of the star.

The planetary nebulae ought perhaps to be regarded as stars of still larger diameter. Surrounding the nucleus—a comparatively faint star with an extremely high surface-temperature—is the nebulosity from which these objects derive the second half of their unfortunate name. This is in all probability merely an atmosphere of even greater extent than that surrounding the four stars of our table. Van Maanen has estimated the diameter of the nebulosity of the Ring Nebula in Lyra (fig. 2 of Plate V) to be about four million million miles, while the average diameter of 21 nebulae which he studied comes out at about a light-year, or nearly six million million miles. This nebulosity, however, differs from the atmosphere of an ordinary star in being very nearly transparent; we can see through millions of millions of miles of the Ring Nebula, but can only see a few tens or hundreds of miles into an ordinary star.

At the other extreme of size, the smallest known star, van Maanen's star (p. 288) is just about as large as the earth; over a million such stars could be packed inside the sun and still leave room to spare. And yet its weight is in all probability comparable, not with that of the earth, but with that of the sun; at a guess it may have about a fifth of the sun's weight. To pack

a fifth of the sun's substance inside a globe of the size of the earth, the average ton of matter must be packed into a space of about the size of a small cherry —six tons or so to the cubic inch. The solidity of the earth suggests that its atoms must be packed pretty closely together, but the atoms in van Maanen's star must be packed 66,000 times more closely.

How is it done? As we shall shortly see, there is only one possible answer. The atom consists mostly of emptiness—we compared the carbon atom to six wasps buzzing about in Waterloo Station. Let us break the atom up into its constituent parts, pack these together as closely as they will go, and we see the way in which matter is packed in van Maanen's star. Six wasps which can roam throughout the whole of Waterloo Station can nevertheless be packed inside a very small box.

GIANTS AND DWARFS. There is a continuous series of stars between the limits of weight we have mentioned, and the same is true of the limits of temperature (and so also of colour) and of size.

Within these specified limits I can find you a star of any weight or of any colour or of any size you like. But this does not mean that you may specify the weight *and* colour *and* size of the star you want, and that I will undertake to find it for you; if the weight is right the colour may be wrong, and so on. For instance, if you ask for a red star I can find you a very heavy one or a very light one, but it is no good your asking for one of intermediate weight. So far as we know, red stars of intermediate weight simply do not exist. The same is true as regards size—there are no red stars of intermediate size. As far back as 1905, Professor Hertzsprung of Leiden noticed that the red stars could be divided perfectly sharply into two distinct classes characterised by large and small size—

he called them Giants and Dwarfs. Russell, studying the question further in 1913, confirmed Hertzsprung's earlier conclusions, and shewed that the giant-dwarf division extended to stars of other colours than red.

Imagine that we have a series of coloured ladders, one for each colour of star—red, orange, etc. Take all

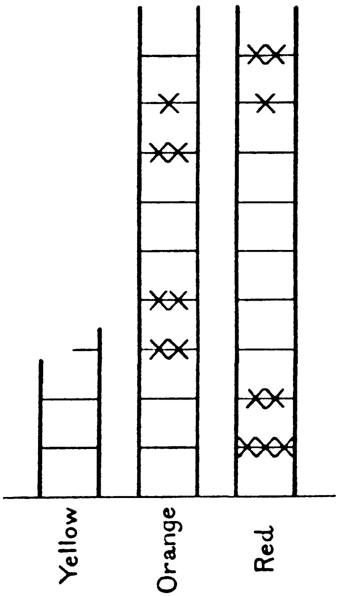

Fig. 20. Stars of different colours arranged in order of luminosity.

the red stars and stand them (in imagination) on the different rungs of the red ladder. Do not merely place them on at random; arrange them in order of their luminosities, placing those of highest luminosity uppermost. Further, if several stars are of about the same luminosity, let them all stand on the same rung of the ladder. To make the arrangement definite, let each rung represent 5 times higher luminosity than the rung

immediately below it, so that each rung has a definite luminosity associated with it*.

With this agreement we are now ready to proceed. We take our red stars and place each on the appropriate rung of the red ladder, and so on for each other colour. The result is shewn diagrammatically in fig. 20, the different stars being represented by crosses.

The red stars will be found to lie as on the right of the diagram, Hertzsprung's division into giants and dwarfs being very clearly marked. The orange stars lie as on the next ladder to the left; as Russell found, the division again appears, but is less marked.

THE RUSSELL DIAGRAM. Let us make ladder diagrams of this kind for each colour of star, and put them side by side in their proper order, so as to represent stars of all possible colours. We obtain a diagram of the kind shewn in fig. 21. This type of diagram was introduced by Russell in 1913, and is now generally known as a Russell diagram.

The letters at the top of the diagram represent spectral types of stars, because these provide a better and more exact working classification than the names of colours. The colours which approximately correspond to the various spectral types are indicated at the bottom of the diagram.

Only a very few sample stars are shewn, but all known stars are found to be concentrated around the positions of these few typical stars. Broadly speaking, there are two distinct and disconnected regions which are occupied by stars. First, and most important, is a region shaped rather like a reversed γ: the central line of this region is marked in by a continuous thick line, following a determination of its position by Redman.

* For purely practical reasons the height is not taken proportional to the luminosity but to its logarithm; without some such device as this it would be impossible to represent the range of more than 1,000,000 to 1 in the observed luminosities of red stars.

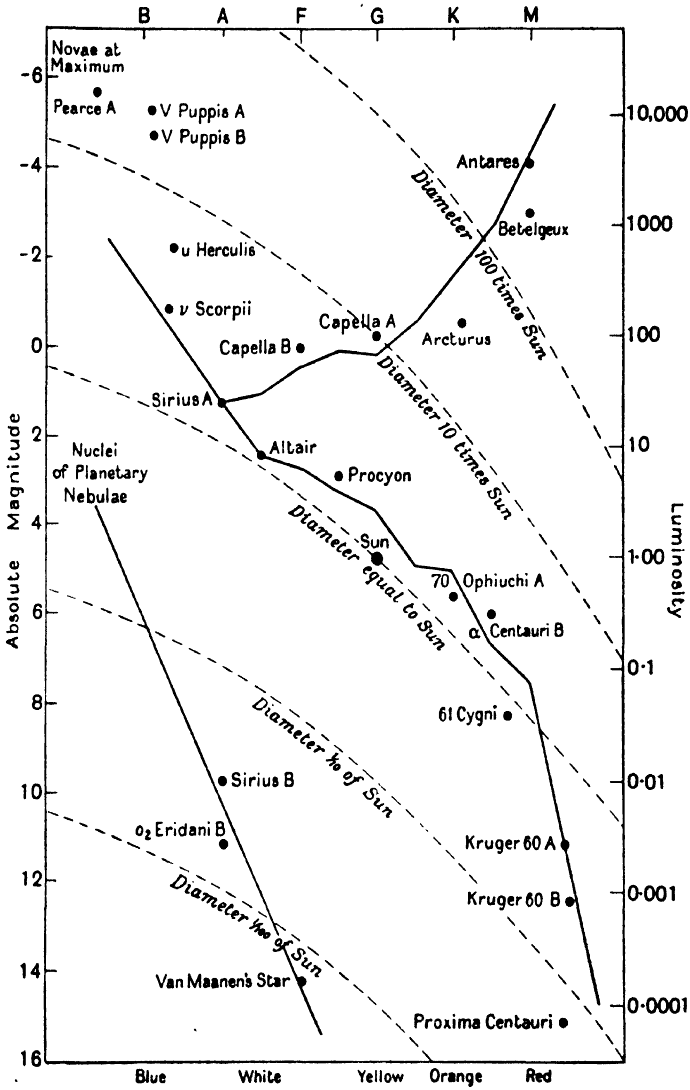

Fig. 21. The Russell diagram.

Second, there is a smaller region near the left-hand bottom corner of the diagram. The stars which occupy this region are very faint, and have far higher surface-temperatures than other stars of similar luminosity.

We have already seen how a star's diameter can be calculated from its surface-temperature and luminosity. This amounts to the same thing as saying that two stars which occupy the same position in the Russell diagram must have the same diameter. Thus there is a definite diameter associated with each point in the diagram, and we can map out stellar diameters in the diagram, just as we can map out heights above sea-level on a geographical map, by a system of "contour lines." In the present case the "contour lines" prove to be a system of almost parallel curves. These lie roughly as shewn by the broken lines in fig. 21, all stars lying on any one line having the same diameter.

This diagram throws a flood of light on the general question of stellar diameters. We see at once that stars of the biggest diameters—100 times the sun's diameter or more—must necessarily be red stars of high luminosity. And in actual fact the stars of large diameter shewn in the table on p. 292 all are red and have very high luminosities; they are red giants.

The majority of the stars in the sky lie in the belt which runs across the diagram from top left-hand to bottom right-hand. This is known as the "main-sequence." The position of this band with reference to the "contour lines" of diameters shews that main-sequence stars are of moderate diameters. The brightest of all may have twenty times the diameter of the sun, while the faintest may have only about a twentieth of the sun's diameter, but they all have diameters which are at least comparable with that of the sun. The sample of stars from near the sun, which we have already dis-

cussed, provides many instances of main-sequence stars; we have, in order of decreasing luminosity:

Star	Luminosity	Diameter (in terms of sun)
Sirius *A*	26·8	1·58
Procyon *A*	5·5	1·80
α Centauri *A*	1·12	1·07
Sun	1·00	1·00
α Centauri *B*	0·32	1·22
τ Ceti	0·32	0·95
ϵ Indi	0·15	0·82
Kruger 60 *A*	0·0026	0·33
,, *B*	0·0007	0·17
Wolf 359	0·00002	0·03

This table shews clearly how stellar luminosity and diameter decrease together as we pass down the main-sequence.

The remaining group of stars in fig. 21, those in the bottom left-hand corner, are generally known as "white-dwarfs." Their position in the diagram shews that their diameters must be excessively small.

In addition to the three stars shewn in the diagram, the faint companion of *o* Ceti is certainly a white dwarf, while Procyon *B* most probably is. A faint star in the double star cluster *h* and χ Persei is also very probably a white dwarf.

These are the only ordinary stars which are at present believed to be white dwarfs, but the extreme faintness of these stars makes them very difficult of detection, so that it is quite likely that they are fairly frequent objects in space.

It seems clear, however, that the nuclei of the planetary nebulae must also be classified as white dwarfs. We have already mentioned the extraordinarily high temperatures of the surfaces of these nuclei. If stars with temperatures such as these lay on the main-sequence, we should expect their luminosities to be

many thousands of times that of the sun—a rough calculation suggests that they might well be about a million times as luminous—in which case their apparent faintness would compel us to suppose them to be very distant objects indeed.

Van Maanen has, however, studied the motions of the planetary nebulae across the face of the sky, and concludes, from the rapidity of their apparent motions, that they must be comparatively near objects of comparatively low luminosity. He estimates the average distance of the twenty-one nebulae he studied at about 4500 light-years, and concludes that they are not enormously more luminous than the sun. When the luminosity is studied visually, the average is found to be ten times that of the sun, but when it is studied photographically, the average is found to be fifteen times that of the sun; the nebular light, being much bluer in colour than ordinary sunlight, affects the photographic plate more vividly—hence the difference in the two estimates of luminosity.

Combining this average luminosity with the known surface-temperature, it is easy to calculate that the average nucleus of a planetary nebula has a diameter which is only about a fifth of that of the sun. The combination of low luminosity and small diameter labels these nuclei as unmistakable white dwarfs.

The following table shews the luminosity and diameter of representative stars of this class:

Star	Luminosity	Diameter (in terms of sun)
Nucleus of planetary nebula	10	0·2
Sirius *B*	0·1	0·05
o_2 Eridani *B*	0·008	0·02
van Maanen's star	0·00016	0·009
Procyon *B*	0·00008	?

In the table on p. 299, the main-sequence stars were intended to be arranged in the order of luminosity, but this happens also to be the order of weights. The weights of three of the stars are unknown; those of the remainder are as follows:

Star	Luminosity	Weight (in terms of sun)
Sirius *A*	26·3	2·45
Procyon *A*	5·5	1·24
α Centauri *A*	1·12	1·14
Sun	1·00	1·00
α Centauri *B*	0·32	0·97
Kruger 60 *A*	0·0026	0·25
,, *B*	0·0007	0·20

Like the luminosities, the weights fall off steadily as we pass down the main-sequence, although, as already remarked, weight falls far less rapidly than luminosity.

The only stars whose weights can be measured directly are the components of binary systems, and these are relatively few in number. Seares found, however, that the weights of binary systems conformed to the law of equipartition of energy already explained in Chapter III, so that it is highly probable that other stars which are not binary also conform, for it is difficult to imagine any reason why binary systems should attain to a state of equipartition sooner than other stars. It will be remembered that this state is defined by a purely statistical law connecting the weights and speeds of motion of stars, so that the fact that a system of stars has attained this state can give no information as to the weight of an individual star whose speed is known, but makes it possible to determine the average weight of any group of stars in terms of their average speeds of motion. In 1922 Seares used this method to estimate the average weights of stars of different assigned luminosities and spectral

types—in other words, the average weights of the stars represented at the various points in the diagram of fig. 21. The results he obtained are shewn by the thick curved lines in fig. 22. The arrangement of these curves

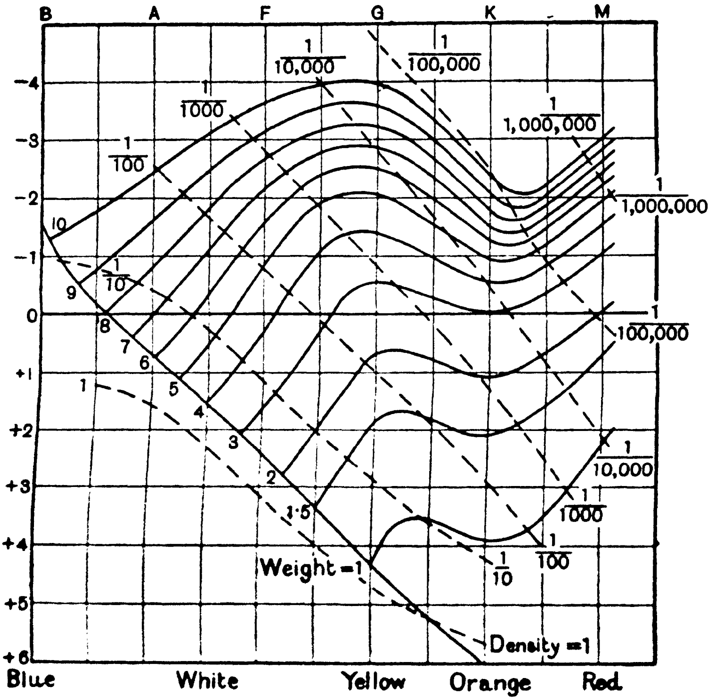

Fig. 22. Stellar weights and densities in the Russell diagram, according to Seares.

confirms the inference we have drawn from a few selected stars; the weight of main-sequence stars falls off steadily as we pass down the sequence from high luminosity to low.

This is more fully confirmed by an investigation which Eddington published in 1924. He found that throughout a considerable range of physical conditions

(which did not, however, include white-dwarf stars), a star's luminosity depended almost entirely on its mass, high luminosity of course being associated with great mass and *vice-versa.*

The curved lines in fig. 22 specify the average weight of the stars represented at each point in the Russell diagram and the diameters are already known from fig. 21. From these two data the mean density of the star can of course be calculated. The mean densities as calculated by Seares are shewn by the broken lines in fig. 22.

This completes our collection of observational material. We now turn to the far more difficult problem of discussing what it all means. Here we leave the firm ground of ascertained fact, to enter the shadowy morasses of conjecture, hypothesis and speculation. The questions we shall discuss are some of the most interesting in the whole of astronomy, to which it must be admitted that science has so far obtained only lamentably dusty answers. The reader who is hot for certainties may prefer to read something other than the remainder of the present chapter.

THE PHYSICAL CONDITION OF THE STARS

The foregoing collection of observational data has provided abundant proof that stars to certain specifications do not exist at all. To put the same thing in another way, there are certain regions in the Russell diagram which are wholly unoccupied by stars.

To take the most conspicuous instance of all, there are no stars at all to the left of the main-sequence in the Russell diagram (fig. 21), until we come to the quite detached group of white dwarfs. Why are there no stars in intermediate conditions? Why, to make the example still more precise, does no star exist of the same colour

as Sirius but with only a tenth of its luminosity? Why do we have to go down to the white dwarf o_2 Eridani *B*, with a luminosity of only a ten-thousandth of that of Sirius, before we can find a star to match Sirius in colour?

A hypothesis which occurs naturally to the mind is that the main-sequence stars and the white dwarfs may form distinct groups because they are of entirely different ages—they may represent distinct creations. Yet this hypothesis does not appear to be tenable.

There are six stars in all which are either known or suspected to be white dwarfs. Four of these are components of a binary system, and in every case the other component is a main-sequence star or (in the case of *o* Ceti) a red giant. We have already seen how rare it is for two stars to approach near to one another in space. It must be an almost inconceivably rare event for two stars, originally moving as independent bodies, so to meet in their random wanderings, that the big one "captures" the little one, and they henceforth journey together through space. For it can be shewn that, for such an event to occur, something more than a close approach is needed; a close approach must take place in the presence of yet a third star, so that no fewer than three stars must chance to come near one another simultaneously in their wanderings through the vast emptiness of space. It is almost inconceivable that this should happen in a single instance, but it is straining the probabilities too far to suppose that it has happened in the case of every single known white dwarf but two. Thus we have to suppose that the white dwarfs and their more normal companions have been together since birth, and so were born at the same time out of the same nebula.

The difference between white dwarfs and main-sequence stars cannot, then, be a mere difference of

age, and it would seem as though there must be some physical reason militating against the existence of stars in intermediate conditions. Taking a more general view of the question, we are led to investigate whether the absence of stars built to certain specifications can be attributed to such stars needing physical properties which nature cannot provide. This leads directly into the general question of the structure and mechanism of the stars.

THE INTERNAL CONSTITUTION OF THE STARS

Most investigations on the structure of the stars have proceeded on the supposition that their interiors are gaseous throughout. Without accepting this supposition as final truth, we may adopt it for the moment, for the purely opportunist reason that it provides the most convenient line of approach to an excessively difficult problem.

A mathematical theorem, generally known as Poincaré's theorem, proves to be of the utmost service in discussing the internal state of a gaseous star. We have seen how Helmholtz thought that the energy of the sun's radiation might come from the sun's contraction, each layer falling in upon the next inner layer as the latter shrunk, and transforming the energy set free by its fall into heat and light. It is easy to estimate how much energy would be set free by a contraction of this kind. For instance, Lord Kelvin calculated that the contraction of the sun, as it shrunk from infinite size to its present diameter of 865,000 miles, would liberate about as much energy as the sun now radiates in 50 million years. In terms of ergs, the sun's shrinkage would liberate 6×10^{48} ergs of energy.

Poincaré's theorem states that the total energy of

motion of all the molecules in any gaseous star whatever is equal to precisely half the total energy which the star would have liberated in shrinking down to its present size. The theorem is true quite independently of whether the star ever has so shrunk or not: nothing is involved but the present state of the star.

One consequence of the theorem is that the further a gaseous star shrinks, the hotter it becomes; if a star shrinks to half its present size, the total energy set free by its shrinkage from infinite size is doubled, so that the total energy of motion of its molecules is doubled, and therefore its average temperature is doubled. This is a special case of what is generally known as Lane's law.

Let us concentrate, for the moment, on the special case of the sun. Poincaré's theorem tells us that, if the sun is gaseous, the total energy of motion of all its molecules is 3×10^{48} ergs. The next thing we want to know is how many molecules there are in the sun. The sun's weight is 2×10^{33} grammes, but how many molecules are there to a gramme? The answer of course depends on the type of molecule concerned; there are 3×10^{23} molecules in a gramme of hydrogen, 2×10^{22} in a gramme of air and only $2{\cdot}5 \times 10^{21}$ in a gramme of uranium.

TEMPERATURE. If we suppose the sun to be made of air, it must consist of 4×10^{55} molecules, and as the total energy of motion of all these molecules is 3×10^{48} ergs, it follows that their average energy of motion must be $7{\cdot}5 \times 10^{-8}$ erg. Now this energy is only attained at a temperature of 375 million degrees, so that this ought to be the *average temperature of the interior* of the sun, if it were made of air. In 1907 Emden, by a different calculation, found that if the sun were made of air, the *temperature at its centre* would be 455 million degrees. Apart from details, it is clear that the interior temperature of a sun made of air would be one of hundreds of millions of degrees.

So far all study of stellar interiors had proceeded on the supposition that the stars were formed of complete atoms or even molecules. In 1917 I made a simple calculation, of the type already explained on p. 158, and found that the quanta of radiation which fly about at such temperatures would be energetic enough not merely to break up the molecules of air into atoms, but also to strip all, or nearly all, of the electrons from the atoms. At such temperatures each molecule of air would break up into its constituent nuclei and electrons just as surely as, on a hot day, a lump of ice breaks up into its constituent molecules. The electric forces which, in quieter surroundings, would unite the electrons and nuclei, first into atoms and then into complete molecules, find themselves powerless against the incessant hail of rapidly moving projectiles and the shattering blows of quanta of high energy; it would be like trying to build a house of cards in a hurricane. A sun consisting of molecules of air proves to be an inconsistency, a contradiction; our hypothesis has defeated itself, and we must start again from the beginning.

IONISATION. We have already noticed how the different types of stellar spectra correspond in the main to different temperatures; differences of pressure, density and chemical composition must also produce differences in stellar spectra, but these are small in comparison with those produced by differences of temperature. Now as we pass downwards—i.e. away from the surface—in a star, we are in effect passing through layers at different temperatures. Samples of matter taken from these layers would shew different spectra, and these would agree pretty closely with the different types of stellar spectra.

Thus, the different types of stellar spectra ought to give a graphical representation of the different layers

of one and the same star—the sun's surface at a temperature of 6000 degrees shews a spectrum of *G* type, but those slightly deeper layers at which the temperature is 7500 degrees ought to shew a spectrum of *F* type, and yet lower layers should shew spectra of types *A*, *B* and *O* in succession. Now as we pass through these different types of spectra, from the coolest to the hottest in succession, we find evidence of an ever increasing break-up of the atoms. In *M*-type spectra which correspond to the lowest temperatures of all, we find evidence of complete molecules, as for example titanium oxide and magnesium hydride. At higher temperatures, the complete molecules disappear and we come in turn to complete atoms, then to "singly-ionised" atoms from which one electron has been torn off, and finally to "doubly-ionised" atoms from which two electrons have been torn off. In the hottest of ordinary stars the atoms of silicon and oxygen are found to be doubly ionised; in the still hotter nuclei of planetary nebulae, neon is also doubly ionised. And there is little doubt that the spectra of matter at still higher temperatures would shew even higher degrees of ionisation.

This suggests that as we pass inwards in either the sun or any other star, we come to ever-increasing degrees of ionisation. A rough calculation shews that as an adequate preliminary approximation (to be amended as needed), the heat at the centre of the stars breaks up all the molecules and atoms, either completely or nearly so, into their constituent nuclei and electrons. The same is true for all other stars, and this introduces an extreme simplification into the problem of the interior constitution of the stars. We cannot say how many complete molecules there are to a gramme without knowing the nature of the molecules, but once let these molecules be broken up into their constituent

parts, and we can state the total number of these constituent parts with fair accuracy. For we have seen (p. 124) that the atomic weights of all elements except hydrogen are nearly double their atomic numbers. Hence the total number of nuclei and protons in a fully broken-up atom of any substance except hydrogen must be equal to about half the atomic weight of the atom.

Thus, if a star does not contain a great amount of hydrogen, the number of constituent parts in a gramme of fully broken-up stellar matter must be about 3×10^{23}, regardless of the type of molecule from which these parts originate. And when we know the total number of such parts in any star, it becomes easy to calculate the temperature of the star's interior, either from the theorem of Poincaré just mentioned or otherwise. The temperature will be the same as though the star were made of unbroken molecules of hydrogen. Emden calculated in 1907 that the central temperature of a sun of this kind would be about 31,500,000 degrees. Later and more refined calculations by Eddington led to an almost identical temperature, but some still later calculations of my own give the substantially higher figure of 55,000,000 degrees. There is no need for the moment to discuss which of these figures is nearest the truth. Their diversity will indicate what kind of degree of uncertainty attaches to all calculations of this type.

On the other hand, we have seen that the atmospheres of the sun and stars consist mainly of hydrogen, so that it is at least possible that their interiors may also consist largely of hydrogen. In the extreme case in which the sun is supposed to consist entirely, or almost entirely, of hydrogen throughout its whole volume, the foregoing estimates must all be divided by four, and we are left with a central temperature of the order of ten million degrees.

It is easy to see how the physical necessity for such high temperatures arises. The heat which flows away from the sun's surface must first have been brought there from its interior. Heat only flows from a hotter to a cooler place, and a vigorous flow of heat is evidence of a steep temperature gradient. The temperature must rise sharply as we pass from the sun's surface towards its centre, and this rise, continued along the whole 433,000 miles to the centre, must result in a very high temperature indeed being reached there.

The calculated central temperature of from 10 to 55 million degrees so far transcends our experience that it is difficult to realise what it means. To keep a piece of ordinary matter of the size of an ordinary pin-head at a temperature of 50,000,000 degrees—i.e. merely to replenish the energy it loses by radiation from its surface—would need all the energy generated by an engine of three thousand million million horse-power; the pin-head of matter would emit enough heat to kill any one who ventured within a thousand miles of it.

High though this temperature is, calculations shew that it would not suffice to break up the stellar molecules completely. It would strip the atoms of all their electrons down to the K-rings (p. 151), but these would remain intact. It needs temperatures even higher than those we are now considering to strip the K-ring electrons from the nucleus of an atom. This result is true for the whole range, from about 30 to 60 million degrees, within which the temperature of the sun's centre is most likely to lie, and it is true almost independently of the atomic weight or atomic number of the atoms of which we suppose the sun to be built.

Thus we may think of the central parts of the sun as consisting of a collection of atoms stripped down to their K-rings, but not beyond, flying about independently, more or less like the molecules of a gas, and

with them, also flying about like the molecules of a gas, all the stripped-off electrons which originally formed the *L*-ring, the *M*-ring, etc., of the atoms, the whole being at a temperature of somewhere between 30 and 60 million degrees. As we pass outwards towards the sun's surface we come to lower temperatures, at which the atoms are less completely broken up. Finally, close to the sun's surface, we may meet atoms which are completely formed except perhaps for one or two of their outermost electrons.

When the internal constitution of other stars is investigated in the same way, all main-sequence stars are found to have about the same central temperatures as the sun. Moreover, this is not the only property which they have in common. Fig. 22, which exhibits Seares' calculations of mean stellar densities, shews that the main-sequence stars are all of approximately the same mean density, except for comparatively small deviations at the two extremities.

The mean density of the sun is 1·4, which means that the average cubic metre in the sun contains 1·4 ton of matter. At the sun's centre, the density may perhaps be 100 times this, so that a cubic metre there contains about 140 tons of matter. For comparison, a cubic metre of lead contains only about 11 tons. If all stars were built on the same model as the sun, any two stars which had the same mean density would also have equal densities at their centres. But in stars having several times the weight of the sun, a new factor comes into play, namely pressure of radiation—the pressure which radiation exerts in virtue of the weight it carries about with it. In most stars this pressure is insignificant in comparison with the pressure produced by the impact of material atoms and electrons, but in very massive stars it is large enough to influence the structure of the star. It is to this that the very massive

stars whose diameters are tabulated on p. 292 owe their abnormally large size. It is a general consequence of the disturbing effects of radiation-pressure, that the weight of a very massive star is far more concentrated in its central regions than that of a lighter star, so that if a light and a massive star have the same average density, the latter will have by far the higher density at its centre. When this disturbing factor is allowed for, all stars in the upper part of the main-sequence are found to have approximately the same densities in their central regions, a density about equal to that at the centre of the sun, which we may estimate at 140 tons to the cubic metre. And we have already seen that the central regions of these stars have also approximately the same temperatures as the centre of the sun, whence it follows that their physical conditions are all substantially the same. Thus, the atoms in the central regions of all these stars must be broken down to the same extent as the atoms in the central regions of the sun. The *K*-rings of electrons survive intact, but the outer rings are transformed into a hail of electrons flying about like independent molecules.

With sufficient accuracy for our present purpose, all the stars on the main-sequence, except perhaps those at its extreme lower end, may be supposed to be in the same physical condition. On account of this property, the main-sequence forms an admirable base-line from which to carry out a survey of the Russell diagram in respect of the physical conditions of stellar interiors.

We notice from fig. 21 that a star to the right of the main-sequence in the Russell diagram has a greater diameter than a main-sequence star of the same weight. Consequently the energy it would emit in shrinking to its present diameter is less, and hence its molecular energy of motion is less (by Poincaré's theorem). It follows that its internal temperatures are lower, and its

atoms are less completely broken up. Calculation shews that red giants such as Antares can only have central temperatures of from one to five million degrees, so that their atoms probably retain intact not only their K-rings of electrons, but also their L-rings and part at least of their M-rings.

To the left of the main-sequence we come to a region in which stars, if they occurred at all, would have shrunk further, and so would have higher temperatures and more thoroughly broken atoms. Actually no stars are encountered until we come to the white dwarfs. Calculation shews that the central temperatures of these must be many hundreds of millions of degrees at least, and that their atoms must be stripped of electrons right down to the nuclei. Except for a small number of atoms which may have escaped this general fate, the stellar matter must consist of nuclei stripped absolutely bare, and of free electrons, all flying independently through the star. The high densities of these stars provide a convincing proof of the accuracy of this result. The mean density of Sirius B is certainly over 10,000, while that of van Maanen's star is probably over 300,000. There is no way in which matter can be packed as closely as this, except by stripping the atoms of electrons right down to their bare nuclei.

The clearest general impression we can form of the Russell diagram in terms of physical condition is probably obtained as follows:

We think first of two detached bands of stars: one, the white dwarf group, formed by stars in which all the electrons are torn off the atoms; and the other, the main-sequence, formed of stars in which the atoms are still surrounded by their K-rings of electrons, while all exterior rings have been torn off. Starting from about the middle of the main-sequence is the spur branch leading up to the red giants, as shewn in fig. 21. As we

pass along this, the internal temperatures of the stars decrease, so that the stellar atoms are less broken up than in main-sequence stars. In the red giants at the extreme end, even *M*-ring electrons may still remain.

STELLAR STRUCTURE

A star, like a house or a pile of sand, is a structure which would collapse under its own weight were it not that each layer is held up against gravity by the pressure which the next inner layer of the star exerts upon it. This pressure is not, like ordinary gas-pressure, the result of the impacts of complete molecules. It is produced in part by the impact of a certain number of atoms which have been stripped of electrons almost or quite down to their nuclei, but to a far greater extent by the impact of a hail of free electrons. A still further pressure is produced by the impact of radiation which, as we have seen, carries weight about with it, and so exerts pressure on any obstacle it encounters; in the more massive stars, this forms an appreciable fraction of the whole pressure, contributing more than half the total pressure in the most massive stars of all. The combined impacts of free electrons, of atoms (or bare nuclei), and of radiation prevent the star from falling in under its own gravitational attraction.

This gives a reasonably good snapshot picture of a star's structure. The corresponding picture of its mechanism is obtained by thinking of the nuclei as α-ray particles, of the free electrons as β-ray particles, and of the radiation as γ-rays (although in most stars the main bulk of the radiation has the wave-length of X-rays). All these thread their way through the star, and, precisely as in laboratory work, the β-rays are more penetrating than the α-rays, and the γ-rays are more penetrating than either.

THE TRANSPORT OF ENERGY IN A STAR. We have seen how the heat of a gas is merely the energy of its molecular motion. Conduction of heat in a gas is usually studied by regarding each molecule as a carrier of energy; when it collides with a second molecule the energy of the two colliding molecules is redistributed between them, and in this way heat is transported from hotter to cooler regions. Each molecule has a power of transport which is jointly proportional to its energy of motion, its speed of motion, and its "free-path"—the distance it travels between successive collisions.

In the interior of a star, there are three distinct types of carrier in action—atoms (or bare nuclei), free electrons and radiation. We can compare their relative capacities as carriers by multiplying up the energy, speeds and free-paths of each. For this purpose the "free-path" of radiation may be taken to be the distance the radiation travels before 63 per cent. of it has been absorbed, since it can be shewn that this is the average distance it carries its energy. On performing the calculation, the carrying capacity of both nuclei and electrons is found to be insignificant in comparison with that of the radiation. The nuclei and electrons may possess the greater amount of energy, but, owing to their feebler penetrating powers, the distance over which they carry it, their free-path, is far less than that of the radiation. Their speed of transport is also less, since radiation transports its energy with the velocity of light. In this way it comes about that practically the whole transport of energy from the interior of a star to its surface is by the vehicle of radiation.

This general principle was first clearly stated by Sampson in 1894. He also shewed how the temperature of any small fragment of a star's interior must be determined by the condition that it receives just as much radiation as it emits, but his detailed applications

were vitiated through his using an erroneous law of radiation. Twelve years later, Schwarzschild independently advanced the same idea, and expressed it in mathematical equations of "radiative equilibrium" which have formed the basis of every subsequent discussion of the problem.

Just because radiation completely outstrips atoms and electrons in carrying energy from a star's interior to its surface, it follows that the build of a star must be determined by the opacity of the matter in its interior. If this is altered, the carrying power of the radiation is altered, and this affects the whole structure of the star. A star whose interior was entirely transparent could not retain any heat at all; its whole interior would be at a very low temperature and the star would be of enormous extent. On the other hand, in a very opaque star, all energy would remain accumulated at the spot at which it was generated, so that the interior temperature would become very high and the star's diameter would be correspondingly small. It is, of course, the intermediate cases which are of practical interest, but the extreme instances just mentioned shew how a star's build depends on its opacity.

Unfortunately it is impossible to obtain any sort of direct measurement of the opacity of stellar matter. We cannot even measure the opacity of terrestrial matter under stellar conditions, since the interiors of the stars are at incomparably higher temperatures than any available in the laboratory. However, we know that the opacity of stellar matter is due to the atoms, nuclei and free electrons of which it is composed checking the onward journey of radiation, and although we cannot obtain a sample of stellar matter, we know fairly definitely how many atoms, nuclei and electrons such a sample would contain. Thus it becomes a matter of theoretical calculation to determine its opacity.

Such a calculation was carried through by Dr Kramers of Copenhagen in 1923, and his results gained general acceptance. More recently Mr Gaunt of Cambridge has made a much more refined calculation, and obtained results which agree very closely with those originally given by Kramers. In so far as these results can be tested in the laboratory, they agree well with observation. And, although there is a big gap between laboratory conditions and stellar conditions, it is difficult to see how Kramers' formula could fail in the stars.

From this formula we can determine the build of the stars completely, or, if the build of the star is supposed to be known, Kramers' formula tells us the rate at which energy will flow to its surface (this depending entirely on the opacity of the star's substance), and this in turn tells us at what rate energy must be generated inside the star for it to be able to remain in equilibrium in the configuration in question. As might be expected, configurations of different diameters are found to require different rates of generation of energy. In nature, a star must adjust its diameter to suit the rate at which it is generating energy; in so doing it fixes not only its diameter but also its surface-temperature, colour and spectral type. If a star's rate of generation of energy were suddenly to change, the star would expand or contract until it had assumed the radius and temperature suited to its new rate of generation of energy.

Let us first consider a star in which the matter is so loosely packed that the electrons and broken atoms move as freely as in a perfect gas, collisions being rare events, and the distances between consecutive electrons and broken atoms being large in comparison with their linear dimensions. It will be convenient to refer to this as the "gaseous" state, because the interior of

the star behaves like a gas with electrons and broken atoms replacing the molecules of an ordinary gas.

If the whole interior of a star is "gaseous" in this sense, detailed calculation shews that large diameters correspond to feeble generation of energy and *vice versa.* Thus, if the stars were wholly gaseous, red giants would be less luminous than main-sequence stars of the same weight. Seares' diagram, reproduced on p. 302, shews that the reverse is actually the case, a red giant generally emitting from 10 to 20 times as much total radiation as an equally massive main-sequence star. This provides evidence against the stars being wholly gaseous; if they were, the thick lines shewn in Seares' diagram would be replaced by straight slant lines, slanting upwards to the left. The wide divergence between such a system of slant lines and the curves shewn in fig. 22 gives some indication of the extent to which the condition of stellar matter diverges from the purely gaseous state.

According to Kramers' theory, the opacity of matter depends on the atomic numbers and atomic weights of the atoms of which it is built, a large clot of matter in the form of a massive atomic nucleus being far more effective in absorbing radiation than a large number of small clots of the same total weight. Everyday terrestrial experience shews that this is so. It is for this reason that the physicist and surgeon both select lead as the material with which to screen their X-ray apparatus; they find that a ton of lead is far more effective in stopping unwanted X-rays than a ton of wood or of iron. If we knew the total intensity of energy emitted by an X-ray apparatus, and the total weight of shielding material round it, we could form a very fair estimate of the atomic weight of the shielding material by measuring the amount of X-radiation which escaped through it.

A very similar method may be used to determine the atomic weights of the atoms of which the stars are composed. A star is in effect nothing but a huge X-ray apparatus. We know the weights of many of the stars, and the rate at which they are generating X-rays is merely the rate at which they are radiating energy away into space. If we could cut each atomic nucleus in a star into two halves, we should halve the opacity of the star, so that radiation would travel twice as far through the star before being absorbed. If the star were wholly gaseous, this would result in its expanding to four times its original diameter, and in its surface-temperature being halved. It follows that we can calculate the atomic weight of the atoms of which a star is composed from the weight, luminosity and surface-temperature of the star.

If we continue to assume, as before, that a star does not consist in large part of hydrogen, then the atomic weights of a number of stars, calculated on the supposition that the stars are wholly "gaseous", come out in practically every case higher than that of uranium, which is the weightiest atom known on earth. They not only prove to be higher, but enormously higher; so high indeed, as to seem utterly improbable. Again the explanation seems to be that the stars are not wholly gaseous. As soon as stellar interiors are supposed to differ substantially from the purely gaseous condition, the calculated atomic weights are reduced enormously. Unfortunately they cannot be determined exactly, since we do not know what correction to make for deviations from the gaseous state.

If on the other hand we start with a supposition that the stellar matter may consist in large part of hydrogen, there is an alternative solution which requires that some stars at least should consist almost exclusively of hydrogen. This may seem improbable,

but cannot be dismissed as absurd since the only stellar matter whose composition we know with any accuracy—namely the atmospheres of the sun and stars—is found to consist almost entirely of hydrogen.

Quite recently a large amount of work has been done on stellar structure, based upon the supposition that the stars have a central core which is not "gaseous," in the special sense defined on p. 318. Many of the conclusions which have been reached have not gained universal, or even general, acceptance by other workers in the subject. Very few would, however, dispute that the matter at the centres of the white dwarf stars must not be treated as an ordinary gas, and it is generally supposed that the central regions of these stars are in the special and peculiar state which is described as a "degenerate gas" in quantum mechanics. When a gas is in this state, the different ingredients of stellar matter, electrons, nuclei and partially formed atoms, do not obey the ordinary gas laws but are packed as closely together as is permitted by the exclusion principle already mentioned (p. 149); in a certain sense the agglomeration is more like a liquid, or even a solid, than like a gas. The opacity is no longer given by the simple formula of Kramers, and the difficulties just mentioned do not arise. The theory of these stars may now be said to be in a fairly satisfactory state.

Unfortunately matters stand very differently with respect to main-sequence stars and giant stars. As very little is known here with any degree of certainty, as opinion is very divided and as the subject is highly technical, it is hardly possible to discuss it here.

STELLAR EVOLUTION

In an earlier chapter we were led to conjecture that the stars were born as flecks of fiery spray thrown off by spinning nebulae, having previously acquired se-

parate existences as condensations in the outer fringes of these nebulae. When they first came into being, these condensations would, from the mode of their formation, necessarily be of all sorts and sizes and weights, subject only to the single restriction that none of their weights could lie below a certain limit. They would all be of extreme tenuity, their density being comparable with that of the nebula itself. Owing to their differences in size and weight, we must imagine that the stars started their existence at different points in the Russell diagram, and we can imagine their evolution represented by a steady progress through this diagram. Thus we may think of the points which represent stars in this diagram as a great army marching along various roads, all of which lead from birth to final extinction. The problem of stellar evolution reduces in effect to that of discovering the lines of march, and explaining why the stars march along these lines rather than others.

Needless to remark, the problem assumes entirely different forms according as we accept the Friedmann-Lemaître cosmology, which limits the ages of the stars to 100,000 million years or so, or some other cosmology, as for instance one of the Einstein-de Sitter cosmologies, which allow the stars to have ages of millions of millions of years.

In the former case the problem of stellar evolution hardly exists at all. A star loses a few million tons of its weight every minute in the form of radiation, but the loss of weight over 100,000 million years is, generally speaking, inappreciable. Thus the weight of the star may be treated as invariable, and if it changes its configuration at all, its line of march must be along one of the lines of constant weight drawn thick in fig. 22. The combination of this with observation would suggest that the majority of stars merely take up a stationary

position at a point on the main-sequence and stay there all their lives, thus retaining their luminosities, diameters and spectral types uniform throughout their lives—we do not know how or by what mechanism.

A less forbidding problem is presented when we assign to the stars the far longer lives which the Einstein-de Sitter cosmologies are now found to permit. In this case the weights of the stars diminish appreciably in the course of their lives, so that the stars cannot in any case stand still—changes of some kind must occur. These changes are always in the direction of decreasing mass, and a glance at fig. 22 will shew that the general trend of the motion in the Russell diagram must be downwards.

Naturally opinion has been inclined to treat those lanes in the Russell diagram which are occupied by stars, as the main marching road. There are two conspicuous roads along which the stellar army may march without entering into regions unoccupied by stars. The first is of course the "main-sequence," which a great number of considerations suggest to be the main line of march of the stellar army. The branch which starts from the red giants in the Russell diagram represents a second possible line of march, a certain number of stars travelling along this branch until they reach the main-sequence as blue or white stars, and then travelling down the lower half of the main-sequence to end as faint red stars passing on to ultimate extinction.

Progress along each of these roads is accompanied by a continuous shrinkage in the size of the star, its diameter steadily decreasing. This is not the same thing as saying that the star's density continually increases, for the star is continually diminishing in weight, so that even if the star's density remained the same, its diameter would decrease. Nevertheless, a study of Seares' determinations of mean densities, as

shewn in the diagram on p. 302, suggests that there is a continuous increase of density, although this becomes very slight in the middle reaches of the main-sequence.

Practically every theory of stellar evolution which has ever been propounded has imagined the march of the stellar army to be of the same general type as that just described, although perhaps present-day opinion is inclined to treat the main-sequence as the principal line of march, whereas earlier theories supposed the youngest stars to march solely along the red-giant branch, only joining the main-sequence with middle age. The first serious theory of all, that of Lockyer, was expressed in terms of branches of ascending and descending temperature, these together forming the last-mentioned line of march in the Russell diagram. In 1918 Russell propounded a theory which again assigned to the stars the lines of march just described, and also attempted a physical explanation, since abandoned, as to why the stars followed these paths rather than others. In 1925 he propounded a new theory, which we must now explain, as to why the stars follow these particular paths.

RUSSELL'S HYPOTHESIS

This theory was based upon the circumstance that the temperatures at the centres of the main-sequence stars are all very nearly equal; Russell calculated that they were uniformly equal to about 32,000,000 degrees. Let us simplify the situation for a moment by imagining it to be an ascertained fact that the temperatures at the centres of *all* stars are precisely the same, say 32,000,000 degrees. If this were a sure fact, it would be natural to conjecture that the stars possessed some kind of controlling mechanism by which they continually adjusted their central temperatures to this exact figure, so that if ever the temperature fell below

32,000,000 degrees the mechanism would come into play and raise the temperature to precisely this amount, while if it increased above this figure, the mechanism would come into play and depress it. Such controlling mechanisms are of course common in engineering practice; there are for instance the safety-valves which keep the pressure in a boiler always uniform, the Watts governor which keeps an engine going always at the same rate of speed, and the thermostat which keeps the temperature of a room constant.

A mechanism is already known for raising the temperature at a star's centre. If a star is not generating any energy at all in its interior, its emission of radiation causes it to shrink, and this, as we have seen (p. 306), causes its temperature to rise. Thus it is easy to keep a star's central temperature up to 32,000,000 degrees by arranging that no energy shall be generated so long as the temperature at the centre is below 32,000,000 degrees, and this is the main hypothesis on which Russell's theory is based. He supposes that no energy at all is generated by matter at temperatures below 32,000,000 degrees, but that, as soon as this temperature is reached, matter begins to generate energy in sufficient quantity to provide for the radiation of a star.

It is far more difficult to imagine how the temperature can be regulated from the other end. A star whose central temperature is below 32,000,000 degrees must be contracting without generating heat. The contraction will not stop dead the moment the critical temperature is attained; its momentum will carry it on until the central temperature substantially exceeds 32,000,000 degrees. As soon as the temperature seriously exceeds 32,000,000 degrees at the centre, that of a substantial piece of the star will be 32,000,000 degrees or higher. There is an obvious danger that this

mass of matter, all at a temperature higher than 32,000,000 degrees, will produce a profusion of heat which will raise the temperature of the star still further, resulting in more and more generation of energy, until finally the whole star disappears in a flash of radiation. Indeed, Russell's theory supposes that matter at 32,000,000 degrees is in a state rather like that of gunpowder at its flash point. Mathematical analysis then shews that a star whose centre is at a temperature of 32,000,000 degrees would be in the state of a keg of gunpowder with a spark at its centre, and—well, "ohne hast, ohne rast" hardly describes the subsequent course of events.

Eddington has suggested that the stability of the stars might be saved by imagining a time-lag between the instant at which matter attains the critical temperature at which energy begins to be generated and the instant at which the main generation of energy occurs. Yet even if this proposed remedy could be made effective, other difficulties remain. As the normal star inhabits the main-sequence, Russell supposed it to be a property of normal matter to annihilate itself at a temperature of about 32,000,000 degrees, the supposedly uniform central temperature of all main-sequence stars. It then became necessary to introduce further special assumptions to explain the luminosity of white dwarfs and of stars on the red giant spur line, because the central temperatures of these stars are very different from 32,000,000 degrees.

Russell met the difficulty of the red giants by supposing that, in addition to containing matter which began to generate radiation at a temperature of 32,000,000 degrees, such stars contained a vast assortment of other types of matter which generated radiation at lower temperatures. These types of matter used themselves up in turn until finally there was nothing

left but the kind of matter which generated energy at 82,000,000 degrees. The star had now become a main-sequence star, and marched steadily down this sequence. At this time the existence of the separate and entirely dissociated branch of white dwarf stars was not so firmly established as now, and the difficulty created by these stars would seem to be almost insuperable.

A consideration of these various difficulties led me to undertake a general mathematical investigation of the problem of stellar stability, and this in turn led me to propound an alternative hypothesis to explain the distribution of stars in the Russell diagram; it is in brief that the unoccupied regions of the diagram represent stars in an unstable condition. I do not know what proportion of astronomers accept this explanation; some, whose opinion I value, do not. I do not think that much so far written in this book would be seriously challenged by competent critics, but it is only fair to say that at this point we are entering controversial ground.

THE HYPOTHESIS OF LIQUID STARS

Let us begin by imagining an enormous number of stars built on all possible plans, out of all kinds of substances. Mathematical investigation shews that some of these stars may be unable to shine with a steady light for either or both of two reasons—they may explode, like a heated keg of gunpowder, or they may have an instability of build, so that they tend to contract or expand without limit. Whether a star escapes the first pitfall or not depends mainly upon the properties of the substance of which it is built; whether it escapes the second depends mainly upon the way it is built. The two pitfalls are not altogether distinct, and when we consider the stability of wholly gaseous stars of enor-

mously great weight, we find that the pits on the two sides of the path merge into one, or at most only a narrow strip of safe ground is left between them. Nevertheless, stars of enormously great weight are known to exist, and continue shining steadily. If, then, these stars are wholly gaseous, they must occupy the one safe spot of ground between the two pits, and this informs us both as to the way they are built and as to the properties of the substance of which they are built.

We find that a wholly gaseous star can only escape both pitfalls if its substance possesses properties which appear very improbable, and contrary to anything of which we have any experience or knowledge in physics; in brief, for such a star to remain stable, the rate at which its matter generates energy must depend on the temperature of the matter. Such a property is in every way contrary to the physical principles explained in Chapter II, as it is to all our experience of atomic behaviour. For, we have already seen (p. 204) that the generation of stellar energy must involve far more fundamental atomic changes, and so involve quanta of far higher energy, than mere radio-active disintegration, and as the latter process is not affected by temperatures such as we find in stellar interiors, it hardly seems possible that the former should be*.

We have, however, already found indications that the stars are not purely gaseous. In the first place, we have seen that purely gaseous masses could not form close binary systems of the type observed in the spectroscopic binaries (p. 241). Such systems can only be formed out of a mass which simulates the properties of a liquid rather than those of a gas; it is not necessary that the whole mass should be liquid, but

* This provides a further objection to Russell's hypothesis, which, to avoid confusion, was not mentioned on p. 325.

there must be a considerable divergence from the state of a pure gas, at any rate in its central regions. Additional evidence to the same effect has been obtained from the diagram of stellar masses (p. 302).

As soon as we admit that the interiors of the stars need not be in a completely gaseous state, the whole situation changes, even a slight departure from the gaseous state being found to impart a great deal of additional stability to the star. If a star of great weight is purely gaseous in its structure, we have seen how the region of stability between the two pitfalls is reduced to a narrow strip, and only by treading this can the star escape the alternative fates of exploding or collapsing. But if the star has a liquid or partially liquid centre, this strip of safe land is so wide that, consistently with stability, the stellar material may have exactly the property that we should *à priori* expect to find, namely, that its generation of energy proceeds, like radio-active disintegration, at the same rate at all temperatures. If the substance of a star possesses this property, the star can be in no danger of violent explosion—a mass of uranium or radium does not explode whatever we do to it. And mathematical analysis shews that if the centre of the star is either liquid, or partially so, there is no danger of collapse; the liquid centre provides so firm a basis for the star as to render a collapse out of the question.

These considerations suggest the two complementary hypotheses:

1. That the generation of energy by stellar matter proceeds spontaneously, like radio-active disintegration, not being affected by the temperature of the star.

2. That the central regions of the stars are not in a purely gaseous state; their atoms, nuclei and electrons are so closely packed that they cannot move freely

past one another, as in a gas, but rather jostle one another about like the molecules of a liquid.

We have already found reasons for thinking that the generation of stellar energy may result from the complete annihilation of matter. If so, our first hypothesis is that this annihilation proceeds spontaneously, the rate of annihilation being the same at all stellar temperatures. This is of course in complete agreement with the general principles of the quantum-theory, for the table on p. 160 shews that no temperature less than two million million degrees ought to have any influence on the process. Incidentally it is also consistent with our conjecture that the cosmic radiation (p. 166) may have resulted from the annihilation of matter in distant astronomical bodies. For the radiation could not retain its observed high penetrating power if it had already penetrated any great thickness of matter; wherever it originated, it must have got out into empty space without much of a struggle, and this is the same thing as saying that it must have originated in matter at a comparatively low temperature. On this view, then, the existence of the highly penetrating radiation would prove that matter can be annihilated in great quantities at quite low temperatures.

There may be a real difficulty in the fact that there can be no appreciable generation of energy in the substance of which the earth is formed. The sun generates about two ergs of energy per second for each gramme of its substance; if the substance of the earth generated energy at even a ten-thousandth part of this rate, its surface would be too hot for human habitation. The obvious way of accounting for the difference is by saying that the sun is hot, and the earth cool, but our present hypothesis makes this impossible. We have rather to suppose that the interior of the sun consists of different atoms from those of the earth's interior.

Whether this constitutes a fatal difficulty remains to be seen.

THE STABILITY OF STELLAR STRUCTURES

For the present, let us tentatively accept the hypothesis that the generation of stellar energy occurs spontaneously, like the disintegration of radio-active atoms. The atoms which are responsible for the light and heat of the stars may be regarded as super-radio-active atoms which spontaneously change part or all of their substance into radiation.

On this view of the mechanism of generation of stellar energy, we have already seen that a star can only continue to shine steadily if its central regions are not in a purely gaseous condition. A star built on foundations of highly compressible gas meets the same fate as a house built on sand: it collapses. A purely gaseous star is a dynamically unstable structure, and must continually contract until the atoms in its central regions are so closely packed that their state can no longer be regarded as gaseous. Then, and then only, can the star exist permanently as a stable structure. Thus, the central regions of any actual permanent star, the sun for instance, must be in a state which for brevity we may describe as liquid. The first hypothesis on p. 328 is seen to imply the second.

Now let us imagine the sun to be expanded to ten times its present diameter. This would diminish its density to a thousandth part of its original value. The actual sun is 40 per cent. more dense than water, but the expanded sun would only be as dense as ordinary atmospheric air. The atoms and electrons, having moved ten times farther apart, would be so distant from one another that the new sun might be regarded

as wholly gaseous. Thus, it would be dynamically unstable and could not remain in its wholly gaseous state.

Our imaginary expanded sun is of course no longer a main-sequence star in the Russell diagram. In expanding the sun to ten times its present size we move it off the main-sequence into a region entirely vacant of stars—in fact, into the great gulf which lies between the red giants and the red dwarfs (see fig. 21, p. 297). Thus, it appears that even if we deliberately place a star in this region, it does not stay there but immediately contracts until it gets on to the main-sequence. May not this explain why the region in question is untenanted by stars?

Next let us imagine the sun *contracted* to a tenth of its present diameter, so that its atoms and electrons move ten times nearer to one another. Its mean density is thereby increased from 1·4 to 1400 times that of water, and its central density from about 140 to 140,000. You may check me here by pointing out that if the sun is already in a liquid state it cannot be compressed to any such extent—a liquid cannot usually have its density increased a thousand-fold. But we have already noticed that halving a star's diameter doubles its temperature throughout. In the same way reducing a star's diameter to a tenth increases its temperature ten-fold, so that the sun's central temperature will be increased from, say, 50 million degrees to 500 million degrees. And at this latter temperature atoms hardly exist any longer as such—the stellar matter consists almost entirely of free electrons and nuclei. And these are so minute, that the increase of the sun's mean density from 1·4 to 1400 times the density of water is not only possible, but leaves the sun's substance in a state which may best be described as gaseous. Once again, then, the

new sun is dynamically unstable. It would be represented by a point well to the left of the main-sequence, near the middle of the unoccupied region between the main-sequence and the white dwarfs, but as it is unstable it cannot maintain its position here. Again we see that even if we place a star in this region it cannot stay there. And, again—may it not be that the reason why this region is unoccupied is that it represents unstable stars?

Once more you may check me. If I have made my point, it has been by the help of the rise of temperature which accompanies contraction. When we imagined the sun to expand, ought we not to have considered the fall of temperature which accompanies expansion? The answer is that we ought, but it would have made very little difference. Lowering the temperature will cause a number of L-rings, and possibly also of M-rings, of electrons to re-form, so that the new atoms will be of larger size, but they will not lose their freedom of motion sufficiently to make the sun stable. It would have been different if we had been discussing a star of 10 or 50 times the sun's weight; then it can be shewn that the re-formation of K- and L-rings would have produced a series of stable configurations. And the spur branch in the Russell diagram exists to provide a home for just such stars.

The whole problem is too complicated to be discussed satisfactorily in this fragmentary way; its proper discussion involves very complicated mathematical analysis. Mathematical discussion shews that the Russell diagram can be divided into regions representing stable and unstable configurations in a manner which is represented very imperfectly, and in part conjecturally, in fig. 28.

The unstable areas are so marked; the remaining areas are stable. The dots which form a sort of back-

ground to the diagram represent 2100 stars whose absolute magnitudes are known through their distances having been determined spectroscopically at Mount Wilson. The observational material is not perfect; for instance, considerable uncertainty attaches to all

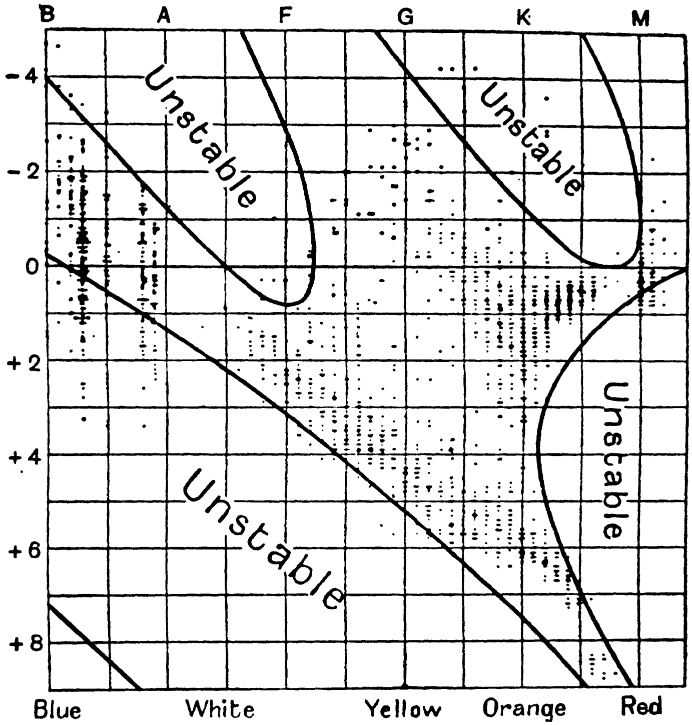

Fig. 23. Stable and unstable configurations in the Russell diagram.

spectroscopic parallaxes of *B*-type stars, and *A*-type stars are almost unrepresented because it is practically impossible to obtain their parallaxes by the spectroscopic method. The theoretical curves are probably still more imperfect, yet, such as they are, they seem

to suggest very forcibly that the occupied and unoccupied regions coincide with those representing stable and unstable configurations; after making all possible allowances for the imperfections both of theory and of observation, too much agreement remains to be explained away as mere coincidence.

Thus the conclusion to which mathematical discussion seems to lead is that the regions in the Russell diagram which are occupied represent stars whose central regions are liquid, or nearly liquid, in the technical sense already explained. All other stars are unstable, so that the corresponding regions in the Russell diagram are necessarily vacant. Thus all the stars in the sky must have liquid, or nearly liquid, centres.

The foregoing hypothesis can be criticised on the ground that the calculated diameters of the K-rings of atoms are so small that the K-ring atoms in the sun's central regions could not possibly be packed closely enough to involve any substantial departure from the gaseous state. Yet it must be borne in mind that we only know the diameters assigned to the K-ring by Bohr's theory (p. 146), and that no one any longer contends that this theory gives a true picture of the atom. It provides a good working model within limits, but we do not know where the limits end. The only practical experience we have of K-ring atoms is with helium atoms; Bohr's theory assigns to these a diameter of $0{\cdot}54 \times 10^{-8}$ cm. Yet solid and liquid helium provide a practical illustration of the closeness with which helium atoms can be packed; in these each atom occupies a sphere of diameter 4×10^{-8} cm., or over 400 times the space allotted to it by Bohr's theory. It looks as though we are still far from definite knowledge of the dimensions of K-rings of electrons. This being so, the criticism cannot be regarded as fatal,

although the difficulty to which it draws attention remains.

STELLAR EVOLUTION

Let us now combine the foregoing hypotheses with the supposition that the stars generate their energy by the annihilation of their substance. We shall find we obtain a consistent and not unreasonable scheme of stellar evolution.

We may suppose that when the stars first come into being, they consist of mixtures of atoms of all kinds, some perhaps being so short-lived as to transform themselves almost at once into radiation, and others having such long lives that they may properly be described as permanent. The permanent atoms in a star contribute almost nothing to its energy-generating capacity, and so merely add to its weight. The shortest-lived atoms of all contribute greatly to the star's generation of energy while adding but little to its weight. In general the shorter the life of any type of atom, the greater the proportion of its numbers annihilated per year, and so the greater the amount of energy it generates per ton of weight. Except for a small number of radio-active atoms, the earth must consist entirely of permanent atoms, since, unless terrestrial atoms had enormously longer lives than the average stellar atom, their self-annihilation would make the earth too hot for habitation.

A star begins life with a large proportion of short-lived atoms, and so at first generates energy furiously. As it ages, the shortest lived atoms disappear first, and in so doing reduce the average energy-generation of the star per ton, so that, as a star's weight decreases, so also must its rate of generation of energy per ton. Finally all the atoms with much energy-generating capacity have disappeared, and the star is left, a

shrunken and diminished mass of atoms which have very little capacity for generating radiation.

To put the same thing in another way, the rate at which a star generates energy per ton is proportional to the death-rate in its population of atoms. To say that Sirius generates 16 times as much energy per ton as the sun is only another way of saying that the average atom in Sirius has only a sixteenth of the expectation of life of the solar atoms; their death-rate is 16 times as high. As those types of atoms which have the highest death-rate gradually die off in any star, the average death-rate of the population decreases, or, in other words, as a star ages its capacity for energy-generation per ton decreases.

This agrees with the findings of observational astronomy. The most massive stars not only generate more energy than less massive stars, as is in any case to be expected; they also generate enormously more energy per ton. This is illustrated by the following list of main-sequence stars:

Star	Weight (in terms of sun)	Generation of energy (ergs per gramme per sec.)
Pearce's star *A*	36·3	15,000
V Puppis *A*	19·2	1,000
Sirius *A*	2·45	29
Sun	1·00	1·90
ϵ Eridani	(0·45)	0·26
Kruger 60 *B*	0·20	0·021

Seares' diagram of stellar weights (p. 302) shews that this is a general property of the stars. To repeat our former metaphor, the stars squander their substance lavishly in their youth, while they have plenty left to spend, but parsimony comes over them with old age. Theoretical considerations have now given us an explanation of this phenomenon.

The same diagram shews that two stars of the same weight do not usually have the same luminosity. In general, giant stars on the spur branch leading out to the red giants have substantially higher luminosities than the main-sequence stars of equal weight. We have already noticed how a red giant may emit as much as 10 or 20 times the radiation of an equally massive main-sequence star. The same story is repeated when we pass from the main-sequence stars to the white dwarfs. Main-sequence stars emit enormously more radiation—anything up to 500 times more—than white dwarfs of equal weight. This is illustrated by the three following white dwarfs, which may be compared with the last three stars of the preceding table:

Star	Weight (in terms of sun)	Generation of energy (ergs per gramme) per sec.
Sirius *B*	0·85	0·009
o_2 Eridani *B*	0·44	0·002
van Maanen's star	(0·20)	(0·00055)

We have hitherto supposed generation of energy to be spontaneous and so unaffected by changes of physical conditions. Yet the facts just mentioned seem to suggest that this can hardly be the whole truth of the matter. To state the objection in terms of a concrete instance, Sirius *A* and its white dwarf companion Sirius *B* must in all probability have been born at the same time out of the same nebula (p. 304), yet the former generates more than a thousand times as much energy per ton as the latter. It seems improbable that so great a difference can be attributed to different types of atoms; the common origin of the two stars almost precludes this. We know that the atoms are in different physical conditions in the two stars; in Sirius *A* they have retained their *K*-rings intact, while in Sirius *B*,

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o_2 Eridani *B*	0·44	0·002
van Maanen's star	(0·20)	(0·00055)

We have hitherto supposed generation of energy to be spontaneous and so unaffected by changes of physical conditions. Yet the facts just mentioned seem to suggest that this can hardly be the whole truth of the matter. To state the objection in terms of a concrete instance, Sirius *A* and its white dwarf companion Sirius *B* must in all probability have been born at the same time out of the same nebula (p. 304), yet the former generates more than a thousand times as much energy per ton as the latter. It seems improbable that so great a difference can be attributed to different types of atoms; the common origin of the two stars almost precludes this. We know that the atoms are in different physical conditions in the two stars; in Sirius *A* they have retained their *K*-rings intact, while in Sirius *B*,

the white dwarf, they are completely broken up into bare nuclei and free electrons. If the two components of Sirius consist of essentially the same types of atoms, as their common origin would lead us to expect, then it would seem that the enormous difference in the rates at which these atoms generate energy must depend on the different physical conditions of their atoms.

This is in accordance with the very speculative conjectures mentioned in Chapter III. We there supposed stellar energy to be generated through electrons coalescing with protons; protons exist only in atomic nuclei, and purely physical considerations led to the conjecture that the only electrons which can coalesce with a particular proton are those which are momentarily describing orbits around the nucleus in which the proton resides. A study of stellar structure supports this hypothesis, for it appears that if energy could be generated by free electrons falling into nuclei, the whole star would be unstable and would explode in a flash of radiation. On this hypothesis, a star in which only a few atoms have any electrons left in orbital motion can of course generate but little energy. This at once explains the feeble energy-generating powers of the white dwarfs, and also may give an inkling as to why the red giants, in which L- and M-rings of electrons survive, generate more energy than main-sequence stars of equal weights.

There is no reason why a similar condition should not occur in more massive stars—as for instance the nuclei of the planetary nebulae (p. 300)—so that stars of great mass may be preserved to an age they could not otherwise attain (p. 203).

On the hypothesis just considered, a star alters both its emission and its generation of energy on changing its diameter. As it ages and its weight decreases, it

continually has to pick out new configurations such as make its emission of energy equal to its internal rate of generation of energy. The same star may be a red giant, a main-sequence star and a white dwarf in turn. A star has so large a range of rates of generation, according as it has few or many electrons left in orbital motion, that it is likely always to be able to find a configuration of equilibrium. At any rate all the stars in the sky appear to have done so, with the possible exception of the Cepheid and long-period variables which appear to be continually expanding and contracting as though they could not hit upon a diameter at which their income and expenditure of energy would just balance.

Whatever uncertainties there may be as to the earlier stages of a star's existence, astronomers generally regard ordinary white dwarfs as the final stage in stellar evolution. There is general agreement that they are stars with central temperatures so high that their atoms are stripped bare of electrons, but there is no general consensus of opinion as to why stars shrink to this condition.

On the liquid star hypothesis, the unoccupied regions in the Russell diagram represent unstable configurations. Usually a slight loss of weight by a star merely moves it to a new position in the diagram contiguous to the old one. Sometimes, however, this slight move may happen to carry the star into an unstable region of the diagram, in which case it will hurriedly traverse this region, until finally it ends up in some entirely different stable configuration.

The liquid star hypothesis explains the white dwarf state quite simply as the final state to which a star shrinks cataclysmically when its generation of energy is no longer sufficient to entitle it to a place in the main-sequence. In this state the star radiates so little

energy that annihilation and decay are almost entirely checked. We have seen that if the sun went on radiating at its present rate for 15 million million years, its whole weight would be transformed into radiation. By contrast, van Maanen's star can, and probably will, go on radiating at its present rate for 15 million million years without losing more than about a thousandth part of its present weight. We may think of the white dwarf state as a final state from which change and decay have so nearly disappeared that a star which shrinks to this state acquires a new lease of life for a period of thousands of millions of millions of years—we can only wonder to what purpose.

EDDINGTON'S THEORY

Eddington has advocated a very different view of stellar evolution. He published an important theoretical investigation in 1917, which contained his famous "mass-luminosity" law. In its original form, this asserted that if a star was "gaseous"—in the technical sense explained on p. 318—throughout its substance, then its luminosity would depend on its mass, but on nothing else.

It followed that a newly born star would rapidly assume the luminosity which this law assigned to it, generating radiation at a rate which would depend solely on its total mass. Generally speaking, there will only be one diameter for a star which will be consistent with its discharging radiation at this assigned rate, so that the star would immediately assume this diameter. According to Eddington's preliminary theory, this diameter must be precisely that of a main-sequence star of the mass in question, and in this way the main sequence is mapped out.

The theory, in this form, gave no account of either

white dwarfs or red giants, and obviously many details remained to be worked out. Nevertheless, its rather startling simplicity gained it many adherents.

It was based on certain assumptions as to stellar opacity, which it was difficult to reconcile with the subsequent investigations of Kramers to which we have referred (p. 317). These shewed that (apart from very special and wholly improbable cases) the luminosity of a "gaseous" star must depend on its surface-temperature as well as on its mass. The "mass-luminosity" law accordingly had to be amended into a "mass-luminosity-temperature" law. This could be represented graphically in a diagram somewhat similar to the observational diagram of Seares shewn in fig. 22. The curves shewing all the configurations possible for a star of assigned mass did not, however, agree with the observational curves shewn in this diagram, but slanted in the opposite direction.

The theory accordingly shewed that a star of assigned mass could have any luminosity whatever; it could emit any desired amount of radiation by adjusting its diameter to a suitable size. Thus, the theory was no longer able to predict what amount of radiation a star of assigned mass would emit—this might be anything from zero to infinity, except of course that extreme values might be excluded as corresponding to ridiculous or impossible diameters for the star. But apart from this limitation, which is of course common to all theories of stellar structure, the theory was unable to fasten any particular diameter on to a star, and so could give no explanation of the existence of the main-sequence, or of the arrangement of stars in the Russell diagram; it led to no theory or explanation of stellar evolution at all.

MILNE'S THEORY

This theoretical work of Eddington's has recently been very vigorously challenged by Milne, who advocates a theory of stellar evolution which, in its main lines, is very similar to (if not indistinguishable from) the theory I had previously advocated, which has already been explained (pp. 326–334). Many details of Milne's theory remain to be worked out, and it can hardly yet be said to have attained a final form.

CHAPTER VI

Beginnings and Endings

We have seen how the solid substance of the material universe is continually dissolving away into intangible radiation. The sun weighed 360,000 million tons more yesterday than to-day, the difference being the weight of 24-hours' emission of radiation which is now travelling through space, and, so far as direct observation goes, is destined to journey on through space until the end of time. The same transformation of material weight into radiation is in progress in all the stars, and to a lesser degree on earth, where complex atoms such as uranium are continually changing into the simpler atoms of lead and helium, and setting radiation free in the process. But against the sun's daily loss of weight of 360,000 million tons, the earth is only losing weight from this cause at the rate of about ninety pounds a day.

CYCLIC PROCESSES. It is natural to ask whether a study of the universe as a whole reveals these processes as part only of a closed cycle, so that the wastage which we see in progress in the sun and stars and on the earth is made good elsewhere. When we stand on the banks of a river and watch its current ever carrying water out to sea, we know that this water is in due course transformed into clouds and rain which replenish the river. Is the physical universe a similar cyclic system, or ought it rather to be compared to a stream which, having no source of replenishment, must cease flowing after it has spent itself?

THERMODYNAMICS

To this question, the wide scientific principle known as the second law of thermodynamics provides an answer in very general terms. If we ask what is the underlying cause of all the varied animation we see around us in the world, the answer is in every case, energy—the chemical energy of the fuel which drives our ships, trains and cars, or of the food which keeps our bodies alive and is used in muscular effort, the mechanical energy of the earth's motion which is responsible for the alternations of day and night, of summer and winter, of high tide and low tide, the heat energy of the sun which makes our crops grow and provides us with wind and rain.

The science of thermodynamics deals primarily with energy and the various changes which it can undergo. It is based fundamentally on two laws which are generally known as the first and second laws of thermodynamics. These deal respectively with the quantity and quality of energy.

FIRST LAW OF THERMODYNAMICS. The first law of thermodynamics, which embodies the principle of "conservation of energy," teaches that energy is indestructible; it may change about from one form to another, but its total amount remains unaltered through all these changes, so that the total energy of the universe remains always the same. As the energy which is the cause of all the life of the universe is indestructible, it might be thought that this life could go on for ever undiminished in amount.

AVAILABILITY OF ENERGY. The second law of thermodynamics rules out any such possibility. Energy is indestructible as regards its amount, but it continually changes in form, and generally speaking we may compare the two directions of change to journeys

uphill and downhill. And it is the usual story. The descent is easy; but to retrace the steps—this is so difficult that we rightly treat it as impossible and think of energy as passing only in the one direction.

For instance, both light and heat are forms of energy, and a million ergs of light-energy can be transformed into a million ergs of heat with the utmost ease; let the light fall on any cool, black surface, and the thing is done. But the reverse transformation is impossible; a million ergs which have once assumed the form of heat, can never again assume the form of a million ergs of light. This is a special example of the general principle that radiative energy tends always to change into a form of longer, not shorter, wave-length. In general, for instance, fluorescence increases the wave-length of the light; it changes blue light into green, yellow or red, but not red light into yellow, green or blue. Exceptions to the general principle are known, but they are of special type, admitting of special explanations, and do not affect the general principle.

It may be objected that the everyday act of lighting a fire disproves all this. Has not the sun's heat been stored up in the coal we burn, and cannot we produce light by burning coal? The answer is that the sun's radiation is a mixture of both light and heat, and indeed of radiation of all wave-lengths. What is stored up in the coal is primarily the sun's light and other radiation of still shorter wave-length. When we burn coal we get some light, but not as much as the sun originally put into the coal; we also get some heat, and this is more than the amount of heat which was originally put in. On balance, the net result of the whole transaction is that a certain amount of light has been transformed into a certain amount of heat.

All this shews that we must learn to think of energy, not only in terms of quantity, but also in terms of

quality. Its total quantity remains always the same; this is the first law of thermodynamics. But its quality changes, and tends to change always in the same direction. Turnstiles are set up between the different qualities of energy; the passage is easy in one direction, impossible in the other. A human crowd may contrive to find a way round without jumping over turnstiles, but in nature there is no way round; this is the second law of thermodynamics. Energy flows always in the same direction, as surely as water flows downhill.

Part of the downward path consists, as we have seen, of the transition from radiation of short wave-length into radiation of longer wave-length. In terms of quanta (p. 144) the transition is from a few quanta of high energy to a large number of quanta of low energy, the total amount of energy of course remaining unaltered. The downfall of the energy accordingly consists in the breaking of its quanta into smaller units. And when once the fall and breakage have taken place, it is as impossible to reconstitute the original large quanta as it was to put Humpty-Dumpty back on his wall.

Although this is the main part of the downward path, it is not the whole of it. Thermodynamics teaches that all the different forms of energy have different degrees of "availability," and that the downward path is always from higher to lower availability.

And now we may return to the question with which we started the present chapter: "What is it that keeps the varied life of the universe going?" Our original answer "energy" is seen to be incomplete. Energy is no doubt essential, but the really complete answer is that it is the transformation of energy from a more available to a less available form; it is the running downhill of energy. To argue that the total energy of the universe cannot diminish, and therefore the uni-

verse must go on for ever, is like arguing that as a clock-weight cannot diminish, the clock-hand must go round and round for ever.

THE FINAL END OF THE UNIVERSE

Energy cannot run downhill for ever, and, like the clock-weight, it must touch bottom at last. And so the universe cannot go on for ever; sooner or later the time must come when its last erg of energy has reached the lowest rung on the ladder of descending availability, and at this moment the active life of the universe must cease. The energy is still there, but it has lost all capacity for change; it is as little able to work the universe as the water in a flat pond is able to turn a water-wheel. We are left with a dead, although possibly a warm, universe—a "heat-death."

Such is the teaching of modern thermodynamics. There is no reason for doubting or challenging it, and indeed it is so fully confirmed by the whole of our terrestrial experience, that it would be difficult to find any point at which it could be open to attack. It disposes at once of any possibility of a cyclic universe in which the events we see are as the pouring of river water into the sea, while events we do not see restore this water back to the river. The water of the river can go round and round in this way, just because it is not the whole of the universe; something extraneous to the river-cycle keeps it continually in motion—namely, the heat of the sun. But the universe as a whole cannot so go round and round. Short of postulating some sort of action from outside the universe, whatever this may mean, the energy of the universe must continually lose availability; a universe in which the energy had no further availability to lose would be dead already. Change can occur only in the one direction, which leads

to the heat-death. With universes as with mortals, the only possible life is progress to the grave.

Even the flow of the river to the sea, which we selected as an obvious instance of true cyclic motion, is seen to illustrate this, as soon as all the relevant factors are taken into account. As the river pours seaward over its falls and cascades, the tumbling of its waters generates heat, which ultimately passes off into space in the form of heat radiation. But the energy which keeps the river pouring along comes ultimately from the sun in the form mainly of light; shut off the sun's radiation and the river will soon stop flowing. The river flows only by continually transforming light-energy into heat-energy, and as soon as the cooling sun ceases to supply energy of sufficiently high availability the flow must cease.

The same general principles may be applied to the astronomical universe. There is no question as to the way in which energy runs down here. It is first liberated in the hot interior of a star in the form of quanta of extremely short wave-length and excessively high energy. As this radiant energy struggles out to the star's surface, it continually adjusts itself, through repeated absorption and re-emission, to the temperature of that part of the star through which it is passing. As longer wave-lengths are associated with lower temperatures (p. 157), the wave-length of the radiation is continually lengthened; a few energetic quanta are being transformed into numerous feeble quanta. Once these are free in space, they travel onward unchanged until they meet dust particles, stray atoms, free electrons, or some other form of interstellar matter. Except in the highly improbable event of this matter being at a higher temperature than the surfaces of the stars, these encounters still further increase the wave-length of the radiation, and the final result of

innumerable encounters is radiation of very great wave-length. The quanta have increased enormously in numbers, but have paid for their increase by a corresponding decrease in individual strength. If the original very energetic quanta had their source in the annihilation of protons and electrons, then the main process of the universe consists in the energy of exceedingly high availability which is bottled up in electrons and protons being transformed into heat-energy at the lowest level of availability.

Many, giving rein to their fancy, have speculated that this low-level heat-energy may in due course re-form itself into new electrons and protons. As the existing universe dissolves away into radiation, their imagination sees new heavens and a new earth coming into being out of the ashes of the old. Science can give no support to such fancies. She cannot, it is true, prove that the fanciful will not happen—she can only calculate the odds against it happening. And these prove to be so enormous that we may disregard altogether the possibility of its occurrence. Perhaps it is as well; it is hard to see what advantage could accrue from an eternal reiteration of the same theme, or even from endless variations of it.

The final state of the universe will, then, be attained when every atom which is capable of annihilation has been annihilated, and its energy transformed into heat-energy wandering for ever round space, and when all the weight of any kind whatever which is capable of being transformed into radiation has been so transformed.

We have mentioned estimates that matter is distributed in space at an average rate of something like 10^{-30} gramme per cubic centimetre. The annihilation of a gramme of matter liberates 9×10^{20} ergs of energy, so that the annihilation of 10^{-30} gramme of matter

liberates 9×10^{-10} erg of energy. It follows that the total annihilation of all the substance of the existing universe would only fill space with energy at the rate of 9×10^{-10} erg per cubic centimetre. This amount of energy is only enough to raise the temperature of space from absolute zero to a temperature which is still well below that of liquid air; it would only raise the temperature of the earth's surface by about a thousandth part of a degree Centigrade. The reason why the effect of annihilating a whole universe is so extraordinarily slight is of course that space is so extraordinarily empty of matter; trying to warm space by annihilating all the matter in it is like trying to warm Waterloo Station by burning a few specks of dust here and there inside it. As compared with any amount of radiation that is ever likely to be poured into it, the capacity of space is that of a bottomless pit. Indeed, so far as scientific observation goes, it is entirely possible that the radiation of thousands of dead universes may even now be wandering round space without our suspecting it.

Such is the final end of things to which, so far as present-day science can see, the material universe must inevitably come in some far-off age, unless the course of nature is changed in the meantime. Let us now try to peer back towards the beginnings of things.

THE BEGINNINGS OF THE UNIVERSE

As we go forwards in time, material weight continually changes into radiation. Conversely, as we go backwards in time, the total material weight of the universe must continually increase. We have seen how the present weights of the stars are incompatible with their having existed for more than a few millions of millions of years, and that they would need approximately the whole of this enormous period to acquire certain signs

of age which their present arrangement and motions reveal.

We have seen how the break-up of the huge extra-galactic nebulae results in the birth of stars, and have found that the most consistent account of the origin of the galactic system of stars is provided by the supposition that the whole system originated out of the break-up of a single huge nebula, perhaps some 5 to 10 million million years ago.

Let us pause for a moment to compare this with an alternative hypothesis, which some astronomers have favoured, that stars are being created all the time. On this hypothesis we picture the stars as passing in an endless steady stream from creation to extinction, just as men pass in an endless steady stream from their cradles to their graves, a new generation always coming into being to step into the place vacated by the old. On this view Plaskett's star, with about a hundred times the weight of the sun, must be a recent creation, while Kruger 60, with only a fraction of the sun's weight would be very, very old—perhaps 100 million million years older than Plaskett's star.

At present direct observation cannot definitely decide between the two conflicting hypotheses, but it rather frowns upon the "steady stream" view of the stars. In a steady population the number of people in any assigned condition is exactly proportional to the time taken to pass through that condition. Suppose for instance that human beings possess infant teeth for a quarter as long as they possess adult teeth. If an examination of the teeth of a population shewed that four times as many had adult teeth as infant teeth, this would create a *prima facie* expectation that we were dealing with a steady population. If, on the contrary, 100 times as many people were found with adult teeth as with infant teeth, we should conclude

that we were not dealing with a steady population. If other evidence pointed to the population all being of approximately the same age, we should be inclined to accept this and regard the 1 per cent. of cases of infant teeth as cases of arrested development.

We do not judge the ages of stars by their teeth but by their weights and luminosities. And the luminosities of the stars are not found to conform to the statistical laws which would prevail in a steady population of stars. There appear to be so many middle-aged stars and so few infants and veterans as to make the hypothesis of a steady continuous creation hardly tenable.

PRE-STELLAR EXISTENCE. On the whole it seems likely that we must assign ages of 5 to 10 million million years to most or all of the stars in the galactic system. This is as far as we can probe back into time with any reasonable plausibility. The atoms which now form the sun and stars must no doubt have had a previous existence as atoms of a nebula, but we cannot say for how long. The temperatures at the centres of the gaseous extra-galactic nebulae may be, and in all probability are, so high that atoms are stripped bare of electrons and so, on the hypothesis we have already considered, would be shielded from annihilation. We may in fact regard the gaseous centres of nebulae as a sort of "white dwarfs" built on a colossal scale—like the nuclei of the planetary nebulae but incomparably more massive. This fits on to the fact that the nebulae generate very little energy for their weights and so shine very feebly.

We have seen that the weights of two extra-galactic nebulae can be estimated to a reasonable degree of accuracy. The great Andromeda nebula *M* 31 has the weight of 3500 million suns, its total luminosity being that of 660 million suns. The nebula N.G.C. 4594 has the weight of 2000 million suns, and the luminosity of

260 million suns. If the luminosity of the nebulae is produced by the annihilation of their atoms, a simple calculation shews that the atoms in the Andromeda nebula have an average expectation of life of 80 million million years, while the corresponding figure for N.G.C. 4594 is 115 million million years. From these two instances, we may guess that the average life, before annihilation, of the atoms in such nebulae must be of the order of 100 million million years. This calculation cannot claim to be either very convincing or very exact, but it supplies the only evidence at present available as to the probable length of life of matter in the nebular state. We can say that the stars have existed *as such* for perhaps from 5 to 10 million million years, and that their atoms may have previously existed in nebulae for at least a comparable, and possibly for a much longer, time.

Apart from detailed figures, however, it is clear that we cannot go backward in time for ever. Each step back in time involves an increase in the total weight of the matter of the universe, and, just as with individual stars, we cannot go so far back that this total weight becomes infinite. Indeed, a limit may quite possibly be set by considerations which we have already mentioned. The complete annihilation of all the matter now in the universe would raise the temperature of the earth's surface by about a thousandth part of a degree; the annihilation of a hundred thousand times as much matter would raise it by about 200 degrees. We cannot admit that as much radiation as this can be wandering about space. The earth's temperature is determined by the amount of radiation it receives from the sun; it adjusts its temperature so that it radiates away just as much energy as it receives. A small correction is required on account of the earth's radio-activity, but this need not bother us. What would

bother us, and would indeed upset the balance entirely, would be the radiation of a hundred thousand dead universes if this were for ever streaming on to us out of space; in this event the earth's surface would have to rise to a temperature well above that of boiling water before it could restore the balance between the radiation it received and that it emitted. In a word, the radiation of a hundred thousand dead universes would boil our seas, rivers and ourselves.

THE CREATION OF MATTER. All this makes it clear that the present matter of the universe cannot have existed for ever; indeed, we can probably assign an upper limit to its age of, say, some such round number as 200 million million years. And, wherever we fix it, our next step back in time leads us to contemplate a definite event, or series of events, or continuous process, of creation of matter at some time not infinitely remote. In some way matter which had not previously existed, came, or was brought, into being.

If we want a naturalistic interpretation of this creation of matter, we may imagine radiant energy of any wave-length less than $1{\cdot}3 \times 10^{-13}$ cm. being poured into empty space; this is energy of higher "availability" than any known in the present universe, and the running down of such energy might well create a universe similar to our own. The table on p. 160 shews that radiation of the wave-length just mentioned might conceivably crystallise into electrons and protons, and finally form atoms. If we want a concrete picture of such a creation, we may think of the finger of God agitating the ether.

We may avoid this sort of crude imagery by insisting on space, time, and matter being treated together and inseparably as a single system, so that it becomes meaningless to speak of space and time as existing at all before matter existed. Such a view is consonant not

only with ancient metaphysical theories, but also with the modern theory of relativity. The universe now becomes a finite picture whose dimensions are a certain amount of space and a certain amount of time; the protons and electrons are the streaks of paint which define the picture against its space-time background. Travelling as far back in time as we can brings us not to the creation of the picture, but to its edge; the creation of the picture lies as much outside the picture as the artist is outside his canvas. On this view, discussing the creation of the universe in terms of time and space is like trying to discover the artist and the action of painting, by going to the edge of the picture. This brings us very near to those philosophical systems which regard the universe as a thought in the mind of its Creator, thereby reducing all discussion of material creation to futility.

Both these points of view are impregnable, but so also is that of the plain man who, recognising that it is impossible for the human mind to comprehend the full plan of the universe, decides that his own efforts shall stop this side of the creation of matter.

This last point of view is perhaps the most justifiable of all from the purely philosophic standpoint. It is now a full quarter of a century since physical science, largely under the leadership of Poincaré, left off trying to explain phenomena and resigned itself merely to describing them in the simplest way possible. To take the simplest illustration, the Victorian scientist thought it necessary to "explain" light as a wave-motion in the mechanical ether which he was for ever trying to construct out of jellies and gyroscopes; the scientist of to-day, fortunately for his sanity, has given up the attempt and is well satisfied if he can obtain a mathematical formula which will predict what light will do under specified conditions. It does not matter much whether the

formula admits of a mechanical explanation or not, or whether such an explanation corresponds to any thinkable ultimate reality. The formulae of modern science are judged mainly, if not entirely, by their capacity for describing the phenomena of nature with simplicity, accuracy, and completeness. For instance, the ether has dropped out of science, not because scientists as a whole have formed a reasoned judgment that no such thing exists, but because they find they can describe all the phenomena of nature quite perfectly without it. It merely cumbers the picture, so they leave it out. If at some future time they find they need it, they will put it back again.

This does not imply any lowering of the standards or ideals of science; it implies merely a growing conviction that the ultimate realities of the universe are at present quite beyond the reach of science, and may be—and probably are—for ever beyond the comprehension of the human mind. It is *à priori* probable that only the artist can understand the full significance of the picture he has painted, and that this will remain for ever impossible for a few specks of paint on the canvas. It is for this kind of reason that, when, as in Chapter II, we try to discuss the ultimate structure of the atom, we are driven to speak in terms of similes, metaphors, and parables. There is no need even to worry overmuch about apparent contradictions. The higher unity of ultimate reality must no doubt reconcile them all, although it remains to be seen whether this higher unity is within human comprehension or not. In the meantime a contradiction worries us about as much as an unexplained fact, but hardly more; it may or may not disappear in the progress of science.

If some such train of thought may be applied to our efforts to understand the most minute processes of the universe (and it is the common everyday train of

thought of those who are working in this field), then it must surely be still more applicable to our efforts to understand the universe as a whole. Phenomena come to us disguised in their frameworks of time and space; they are messages in cypher of which we shall not understand the ultimate significance until we have discovered how to decode them out of their space-time wrappings. Whatever may be thought about our final ability to decode the difficult messages we have recently received about the ultimate structure of the minutest parts of matter, it seems natural that we should feel some apprehension with regard to those about the structure of the universe as a whole, and particularly those about its beginnings and endings. Often enough the message itself may help us to discover the code in which it reaches us—with sufficient skill we can often do this—but we are now speaking of problems as to when, by whom, and for what purpose, the code was devised. There is no reason why a code message should throw any light on this.

The astronomer must leave the problem at this stage. The message of astronomy is of obvious concern to philosophy, to religion and to humanity in general, but it is not the business of the astronomer to decode it. The observing astronomer watches and records the dots and dashes of the needle which delivers the message, the theoretical astronomer translates these into words —and according as they are found to form known consistent words or not, it is known whether he has done his job well or ill—but it is for others to try to understand and explain the ultimate decoded meaning of the words he writes down.

LIFE AND THE UNIVERSE

Abandoning our efforts to understand the universe as a whole, let us glance for a moment at the relation of life to the universe we know.

The old view that every point of light in the sky represented a possible home for life is quite foreign to modern astronomy. The stars themselves have surface-temperatures of anything from 1650 degrees to 60,000 degrees or more, and are of course at far higher temperatures inside. By far the greater part of the matter of the universe is at a temperature of millions of degrees, so that its molecules are broken up into atoms, and the atoms are broken up, partially at least, into their constituent parts. Now the very concept of life implies duration in time; there can be no life—or at least no life at all similar to that we know on earth—where atoms change their make-up millions of times a second and no pair of atoms can ever stay joined together. It also implies a certain mobility in space, and these two implications restrict life to the small range of physical conditions in which the liquid state is possible. Our survey of the universe has shewn how small this range is in comparison with that exhibited by the universe as a whole. It is not to be found in the stars, nor in the nebulae out of which the stars are born. We know of no type of astronomical body in which the conditions can be favourable to life except planets like our own revolving round a sun.

Now, to the best of our present knowledge, planets must be very rare. We have seen how a single star cannot of itself produce planets. A family of planets must have two parents; it only comes into being as the result of the close approach of two stars, and stars are so sparsely scattered in space that it is an inconceivably rare event for one to pass near to a neighbour. On the

Tidal Theory, explained on p. 255, planets cannot be born except when two stars either collide with one another, or graze one another, or pass within a very few diameters of one another. As we know how sparsely the stars are scattered in space, we can estimate fairly closely how often two stars will approach within this distance of one another. The calculation shews that even after a star has lived its life of millions of millions of years, the chance is still about a hundred thousand to one against its being a sun surrounded by planets.

Even so, if life is to obtain a footing, the planets must not be too hot or too cold. In the solar system, for instance, we cannot imagine life existing on Mercury or on Neptune; liquids boil on the former and freeze hard on the latter. These planets are unsuitable for life because they are too near to, or too far from, the sun. We can imagine other planets which are unsuitable because their substance itself generates energy at such a rate as to make them unsuitable for habitation. The inert atoms which form our earth seem to be the end products of a long series of atomic changes, a sort of final ash resulting from the combustion of the universe. It seems quite likely that such atoms may float to the top in every star, as being the lightest in weight, but it is by no means a foregone conclusion that all planets will consist of nothing but inert atoms, and so will cool down until life can obtain a footing on them. This has happened with our earth, but we do not know how many planets and planetary systems may be unsuited for life because it has not happened with them.

All this suggests that only an infinitesimally small corner of the universe can be in the least suited to form an abode of life. Primaeval matter must go on transforming itself into radiation for millions of millions of years to produce a minute quantity of the inert ash on which life can exist. Then by an almost incredible

accident this ash, and nothing else, must be torn out of the sun which has produced it, and condense into a planet. Even then, this residue of ash must not be too hot or too cold, or life will be impossible.

Finally, after all these conditions are satisfied, will life come or will it not? We must probably discard the at one time widely accepted view that if once life had come into the universe in any way whatsoever, it would rapidly spread from planet to planet and from one planetary system to another until the whole universe teemed with life; space now seems too cold, and planetary systems too far apart. Our terrestrial life must in all probability have originated on the earth itself. What we would like to know is whether it originated as the result of still another amazing accident or succession of coincidences, or whether it is the normal event for inanimate matter to produce life in due course, when the physical environment is suitable. We look to the biologist for the answer, which so far he has not been able to produce.

The astronomer might be able to give a partial answer if he could find evidence of life on some other planet, for we should then at least know that life had occurred more than once in the history of the universe, but so far no convincing evidence has been forthcoming. Some astronomers interpret certain markings on Mars as canals, which they believe to be the handiwork of intelligent beings, but this interpretation is not generally accepted. Again, seasonal changes necessarily occur on Mars as on the earth, and certain phenomena accompany these which many astronomers are inclined to ascribe to the growth and decline of vegetation, although they may represent nothing more than rains watering the desert. There is no definite evidence of life, and certainly no evidence of conscious life, on Mars—or indeed anywhere else in the universe.

It seems at first somewhat surprising that oxygen figures so largely in the earth's atmosphere, in view of its readiness to enter into chemical combination with other substances. We know, however, that vegetation is continually discharging oxygen into the atmosphere, and it has often been suggested that the oxygen of the earth's atmosphere may be mainly or entirely of vegetable origin. If so, the presence or absence of oxygen in the atmospheres of other planets should shew whether vegetation similar to that we have on earth exists on these planets or not.

Oxygen certainly exists in the Martian atmosphere, but its amount is small. Adams and St John estimate that there cannot be more than 15 per cent. as much, per square mile, as on earth. On the other hand, it is either completely absent, or of negligible amount, in the atmosphere of Venus. If any is present at all, St John estimates that the amount above the clouds which cover the surface of Venus is less than a thousandth part of the amount on earth. The evidence, for what it is worth, goes to suggest that Venus, the only planet in the solar system outside Mars and the earth on which life could possibly exist, possesses no vegetation and no oxygen for higher forms of life to breathe.

Apart from the certain knowledge that life exists on earth, we have no definite knowledge whatever except that, at the best, life must be limited to a tiny fraction of the universe. Millions of millions of stars exist which support no life, which have never done so and never will do so. Of the rare planetary systems in the sky, many must be entirely lifeless, and in others life, if it exists at all, is probably limited to a few planets. The three centuries and more which have elapsed since Giordano Bruno expressed his belief in an infinite number of worlds have changed our conception of the universe almost beyond description, but they have not brought

us appreciably nearer to understanding the relation of life to the universe. We can still only guess as to the meaning of this life which, to all appearances, is so rare. Is it the final climax towards which the whole creation moves, for which the millions of millions of years of transformation of matter in uninhabited stars and nebulae, and of the waste of radiation in desert space, have been only an incredibly extravagant preparation? Or is it a mere accidental and possibly quite unimportant by-product of natural processes, which have some other and more stupendous end in view? Or, to glance at a still more modest line of thought, must we regard it as something of the nature of a disease, which affects matter in its old age when it has lost the high temperature and capacity for generating radiation with which younger and more vigorous matter would at once destroy life? Or, throwing humility aside, shall we venture to imagine that it is the only reality, which creates, instead of being created by, the colossal masses of the stars and nebulae and the almost inconceivably long vistas of astronomical time?

Again it is not for the astronomer to select between these alternative guesses; his task is done when he has delivered the message of astronomy. Perhaps it is over-rash for him even to formulate the questions this message suggests.

THE EARTH AND ITS FUTURE PROSPECTS

Let us leave these rather abstract regions of thought and come down to earth. We feel the solid earth under our feet, and the rays of the sun overhead. Somehow, but we know not how or why, life also is here; we ourselves are part of it. And it is natural to enquire what astronomy has to say as to its future prospects.

The central facts which dominate the whole situation

are that we are dependent on the light and heat of the sun, and that these cannot remain for ever as they now are. So far as we can at present see, solar conditions can hardly have changed much since the earth was born; the earth's 2000 million years form so small a fraction of the sun's whole life that we can almost suppose the sun to have stood still throughout it. This of itself suggests that, in so far as astronomical factors are concerned, life may look to a tenancy of the earth of far longer duration than the total past age of the earth.

The earth, which started life as a hot mass of gas, has gradually cooled, until it has now about touched bottom, and has almost no heat beyond that which it receives from the sun. This just about balances the amount it radiates away into space, so that it would stay at its present temperature for ever if external conditions did not change, and any changes in its condition will be forced on it by changes occurring outside. These changes may be either gradual or catastrophic.

The most obvious of the gradual changes is a diminution of the light and heat received from the sun. The sun's loss of weight which results from its emission of radiation causes the earth to recede from it at the rate of about a yard a century, so that after a million million years, the earth will be 6 per cent. farther away from the source of its light and life than now. Even if the sun then radiated as much light and heat as now, the earth would receive 11 per cent. less of this radiation, and its mean temperature would be some 8 degrees Centigrade or so lower than at present. But after a million million years the sun will not radiate as much light and heat as now; it will have lost some 6 per cent. of its present weight through radiation, and, judging from other stars, this loss will probably reduce its

energy-generating capacity by about 20 per cent. This will reduce the earth's temperature by about another 15 degrees, so that after a million million years the inevitable course of events will have reduced the earth's temperature by about 23 degrees Centigrade.

It would be rash to attempt to predict how such a fall of temperature may affect terrestrial life, and human life in particular. Given sufficient time, life has such an enormous capacity for adapting itself to its environment that it seems possible that, even with a temperature 23 degrees Centigrade lower than now, life may still exist on earth a million million years hence. If so, I am glad that my life has not fallen in this far distant future. Mountains and seas, which provide some of the keenest pleasures of our present life, will exist only as traditions handed down from a remote and almost incredible past. The denudation of a million million years will have reduced the mountains almost to plains, while seas and rivers will be frozen packs of solid ice. We may well imagine that man will have infinitely more knowledge than now, but one thing he will no longer know—the thrill of pleasure of the pioneer who opens up new realms of knowledge. Disease, and perhaps death, will have been conquered, and life will doubtless be safer and incomparably better-ordered than now. It will seem incredible that a time could have existed when men risked, and lost, their lives in traversing unexplored country, in climbing hitherto unclimbed peaks, in fighting wild beasts for the fun of it. Life will be more of a routine and less of an adventure than now; it will also be more purposeless when the human race knows that within a measurable space of time it must face extinction and the eternal destruction of all its hopes, endeavours, and achievements.

Without laying too much stress on these visionary

concepts of life a million million years hence, we may nevertheless think of this as the period in round numbers after which the inevitable wastage of the sun's weight is likely to drive life off the earth. Venus, with a mean temperature some 50 degrees higher than the earth, is probably rather too hot for life at present. But after a million million years, the temperature of Venus will have fallen by 30 degrees, and what the earth is now, Venus may perhaps be somewhere between one and two million million years hence. Whether life will then inhabit Venus we cannot know, and it would be futile to guess, but there is at least a chance that as the earth fails, Venus may step into its place. Possibly Venus may be followed by Mercury in due course, but the present evidence is that Mercury is devoid of atmosphere, in which case it is hard to imagine it as a home for life at all resembling that which now inhabits the earth.

So far we have considered only the normal course of events; a variety of accidents may bring the human race to an end long before a million million years have elapsed. To mention only possible astronomical occurrences, the sun may run into another star, any asteroid may hit any other asteroid and, as a result, be so deflected from its path as to strike the earth, any of the stars in space may wander into the solar system and, in so doing, upset all the planetary orbits to such an extent that the earth becomes impossible as an abode of life. It is difficult to estimate the likelihood of any of these events happening, but rough calculations suggest that none of them is likely to happen within the next million million years or so. The more probable dangers are again those connected with the sun's provision of light and heat.

The sun is a main-sequence star, and is moreover very near to the left-hand edge of the main-sequence

in the Russell diagram (p. 297). According to Redman's determinations, which are probably by far the most reliable at present available, the main-sequence belt of stable configurations for stars of the same spectral type as the sun (G 0) extends roughly between stellar absolute magnitudes, 4·88 and 3·54, the former marking the left-hand edge. The sun's present absolute magnitude is estimated as 4·85. Beyond this edge is a region of the diagram which is completely untenanted by stars. We have conjectured that this region is untenanted by stars because the stellar configurations it represents would be unstable. Stars pass through it rapidly until they find a stable configuration, and so end up in a region which can be permanently tenanted by stars. Now the next stable configurations beyond this region are those of the white dwarfs, and as these are less massive as a class than the main-sequence stars, the general trend of stellar evolution appears to be from main-sequence star to white dwarf. On this view the white dwarfs must have previously been main-sequence stars which wandered across the left-hand edge of the band of stable configurations and then fell through the unstable region until they resumed stability as white dwarfs.

A certain danger lies in the fact that the sun is already perilously near to the left-hand edge of the main-sequence; if our conjectures are sound, it may cross this edge, and proceed to contract precipitately to the white dwarf state, probably to a condition resembling that of the faint companion of Sirius. The shrinkage of the sun to this state would transform our oceans into ice and our atmosphere into liquid air; it seems impossible that terrestrial life could survive. The vast museum of the sky must almost certainly contain examples of shrunken suns of this type, and some will have planets like our earth revolving round them.

Whether these planets carry on them the frozen remains of a life which was once as active as our present life on earth we can hardly even surmise.

Another and possibly more serious danger is that the sun's light and heat may increase so much as to shrivel up all terrestrial life. We have seen how "novae" occasionally appear in the sky, temporarily emitting anything up to 25,000 times the radiation of the sun. In many cases the nova has been proved to be an ordinary star which was visible as a very faint star long before it appeared as a nova, flashed into brilliance for a brief span of life, and then lapsed back into commonplaceness, and it seems reasonable to suppose that all novae are of this kind, although the star may often escape detection until it assumes its brilliant nova state. These apparitions are by no means rare; something like six are noticed every year in the galactic system alone, and Dr Lonnqvist of Lund has estimated that, on the average, each star becomes a nova once in every 400 million years. What we would like to know is whether our sun is in danger of becoming a nova—so far as can be told from the geological record, it does not seem to have done so for the last 1000 million years or so.

So far there is no agreement among astronomers either as to the physical causes which turn an ordinary star into a nova, or as to the physical conditions which prevail in novae. Various suggestions are in the field, but none of them wins general acceptance. It seems fairly certain that if our sun were suddenly to become a nova, its emission of light and heat would so increase as to scorch all life off the earth, but we are completely in the dark as to whether our sun runs any risk of entering the nova stage. If it does, this is probably the greatest of all the risks to which life on earth is exposed.

Apart from accidents, we have seen that if the solar

system is left to the natural course of evolution, the earth is likely to remain a possible abode of life for something of the order of a million million years to come.

This is some five hundred times the past age of the earth, and more than a million times the period through which humanity has so far existed on earth. Let us try to set these times in their proper proportion by the help of yet another simple model. Take a postage-stamp, and stick it on to a penny. Now climb Cleopatra's needle and lay the penny flat, postage-stamp uppermost, on top of the obelisk. The height of the whole structure may be taken to represent the time that has elapsed since the earth was born. On this scale, the thickness of the penny and postage-stamp together represents the time that man has lived on earth. The thickness of the postage-stamp represents the time he has been civilised, the thickness of the penny representing the time he lived in an uncivilised state. Now stick another postage-stamp on top of the first to represent the next 10,000 years of civilisation, and keep sticking on postage-stamps until you have a pile as high as Mont Blanc. Even now the pile forms an inadequate representation of the length of the future which, so far as astronomy can see, probably stretches before civilised humanity, unless an accident cuts it short. The first postage-stamp was the past of civilisation; the column higher than Mont Blanc is its future. Or, to look at it in another way, the first postage-stamp represents what man has already achieved; the pile which outtops Mont Blanc represents what he may achieve, if his future achievement is proportional to his time on earth.

Yet we have seen that we cannot count on such a length of future with any certainty. Accidents may happen to the race as to the individual. Celestial

collisions may occur; shrinking into a white dwarf, the sun may freeze terrestrial life out of existence; bursting out as a nova it may scorch our race to death. Accident may replace our Mont Blanc of postage-stamps by a truncated column of only a fraction of the height of Mont Blanc. Even so, our race has an "expectation of life" which must be measured in terms of thousands of millions of years at the very lowest. And the human mind, as apart from the mind of the mathematician, can hardly distinguish clearly between such a period as this and the million million years to which we may look forward if accidents do not overtake us. For all practical purpose the only statement that conveys any real meaning is that our race may look forward to occupying the earth for a time incomparably longer than any we can imagine.

Looked at in terms of space, the message of astronomy is at best one of melancholy grandeur and oppressive vastness. Looked at in terms of time, it becomes one of almost endless possibility and hope. As denizens of the universe we may be living near its end rather than its beginning; for it seems likely that most of the universe had melted into radiation before we appeared on the scene. But as inhabitants of the earth, we are living at the very beginning of time. We have come into being in the fresh glory of the dawn, and a day of almost unthinkable length stretches before us with unimaginable opportunities for accomplishment. Our descendants of far-off ages, looking down this long vista of time from the other end, will see our present age as the misty morning of the world's history; our contemporaries of to-day will appear as dim heroic figures who fought their way through jungles of ignorance, error and superstition to discover truth, to learn how to harness the forces of nature, and to make a world worthy for mankind to live in. We are still too

much engulfed in the greyness of the morning mists to be able to imagine, however vaguely, how this world of ours will appear to those who will come after us and see it in the full light of day. But by what light we have, we seem to discern that the main message of astronomy is one of hope to the race and of responsibility to the individual—of responsibility because we are drawing plans and laying foundations for a longer future than we can well imagine.

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